Vertical Temperature Distribution in the Great Lakes

By H. B. Hachey
Atlantic Biological Station, St. Andrews, N.B.
(Received for publication June 6, 1952)

ABSTRACT

On the basis of temperature observations made in the Great Lakes in the summer months it has been shown that: (*a*) the maximum depth of the thermocline does not exceed 50 feet, (*b*) the temperature gradient within the thermocline may be as much as 26 degrees Fahrenheit in 10 feet, (*c*) the thickness of the surface layer varies considerably with time and position, and can under certain circumstances be entirely removed from an area, and (*d*) the temperature of the deeper waters approximates to that of the maximum density of fresh water.

INTRODUCTION

In June, July and August of 1948 ships of the Royal Canadian Navy made periodic observations of the vertical temperature distribution in Lake Ontario, using bathythermographs for this purpose. In addition, one series of temperature observations was made in a cruise of H.M.C.S. *Portage* from Lake Ontario to Lake Superior. These temperature observations form the subject matter of this report.

DATA

Some Temperature Distributions

Some illustrations of vertical temperature distributions in Lakes Ontario, Huron and Superior are shown in Figure 1. The series of observations in Lake Ontario is shown for June 11, July 3, July 8, July 23 and August 8, and the summer development of the surface layer above the thermocline is thus illustrated. The main feature is the increasing stability of the surface layer with respect to the deeper water as the thermocline becomes fully developed, with a surface temperature of 70°F., a temperature of 66°F. at 40 feet, and a temperature of 40°F. at 50 feet. The main thermocline is thus contained between depths of 40 and 50 feet with a temperature gradient of twenty-six degrees. The lowest temperature recorded to a depth of 300 feet was approximately that of the temperature of maximum density of fresh water.

The illustrations of vertical temperature distribution in Lake Ontario for July 13, July 20, August 10 and July 16 were chosen to illustrate variations in the structure of the surface layer with time and place, and the factors associated with these illustrated features require more information than is at hand.

In Lake Superior, a series of observations was taken as the ship proceeded from Sault Ste. Marie to the head of the lake. In particular, it will be noted that on July 29 at Latitude 47°51′ N. and Longitude 87°29′ W. the temperature was 39°F. from surface to a depth of 250 feet. This temperature is that of the maximum density of fresh water, and it would seem that the surface layer has been entirely removed, allowing upwelling of the deeper water. It may be assumed

J. Fish. Res. Bd. Can., 9 (7), 1952
Printed in Canada.

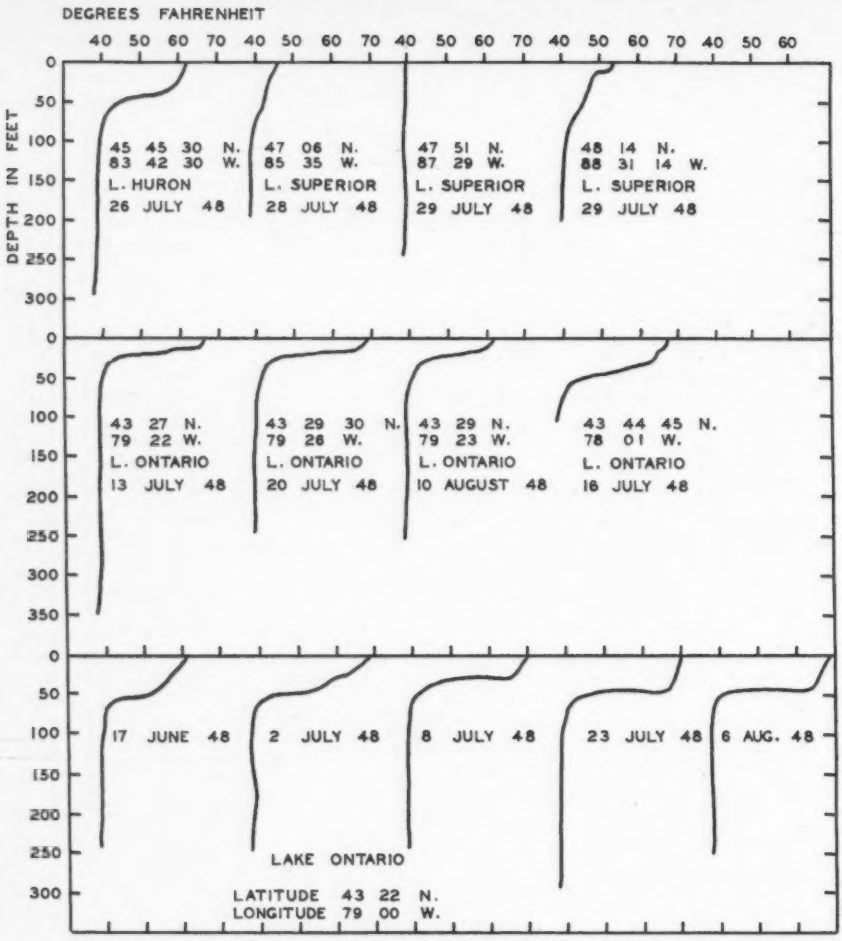


FIGURE 1. Vertical temperature distribution in the Great Lakes.

that the shifting of the surface layer, resulting from wind action, atmospheric pressure distribution and/or seiches, is one of the important phenomena of some of the Great Lakes, and in particular, Lake Superior.

VERTICAL TEMPERATURE SECTIONS IN LAKE ONTARIO

Data are available for the plotting of two vertical temperature sections in Lake Ontario to a depth of 150 feet. These sections are shown in Figure 2, the observations in Section A being taken on July 16 and 17, and those in Section B on July 18 and 19. The depth of the thermocline is indicated for each section. While the depth of the thermocline in Section A varies from 20 feet at Station 3 to

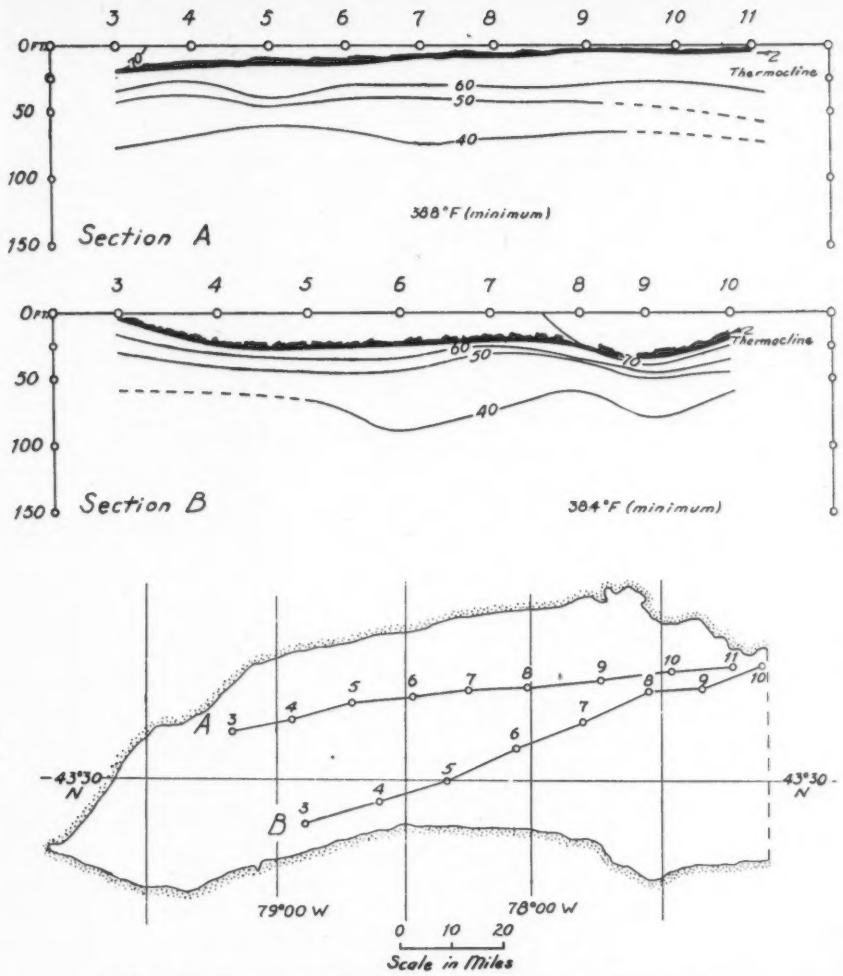


FIGURE 2. Temperature distribution in vertical sections—Lake Ontario.

approximately 7 feet at Station 11, the depths in Section B vary from approximately 7 feet at Station 3 to 35 feet at Station 9. This variation in the depth of the thermocline, both with time and position, is probably the outstanding hydrographic phenomena of the summer season in Lake Ontario and is probably associated with oscillation in the upper layer of water. The 40°F. isotherm which is found at depths between 60 and 90 feet, limits the upper boundary of the deeper waters which approximate the temperature of maximum density of fresh water.

DISCUSSION

From the hydrographic point of view the waters of the Great Lakes offer some interesting aspects for further study. In general, more information is needed for each individual lake in order to determine the details of the temperature cycle at all depths. In particular, the dynamics of the surface layer is a field of considerable interest from the physical point of view, and probably of primary importance to studies of fish life in these waters.

SUMMARY

On the basis of temperature observations made in the months of June, July and August it may be concluded that:

(*a*) the maximum depth of the thermocline in the Great Lakes does not exceed 50 feet;

(*b*) the temperature gradient within the thermocline may be as much as twenty-six degrees Fahrenheit;

(*c*) the thickness of the surface layer, while not exceeding 50 feet during the summer months, varies considerably with time and position, and can, under certain circumstances, be entirely removed from an area;

(*d*) the temperature of the deeper waters approximates to that of the maximum density of fresh water.

ACKNOWLEDGEMENT

This paper is published with the permission of the Canadian Joint Committee on Oceanography.

Surface Temperatures of the Great Lakes[1]

By F. Graham Millar[2]
Meteorological Division, Air Services Branch,
Department of Transport, Canada.
(*Received for publication March 21, 1951*)

ABSTRACT

Thermographs were installed on the condenser intakes of several steamships on the Great Lakes, with which the water temperature was recorded for five to ten years. Averages are presented in tables, maps, and diagrams. The temperature varies considerably over a lake surface in a manner determined by the depths and currents. Standard deviations and serial correlations are found for some of the data.

INTRODUCTION

The programme of observing the water temperatures at the condenser intakes of steamships on the Great Lakes was instituted about 1935 under the direction of Dr. John Patterson, O.B.E., former Controller of the Meteorological Division, Department of Transport. The purpose was to obtain data for a new estimate of evaporation from the Lakes. The information should be useful also for forecasting the visibility and air temperature, and to some extent, precipitation in regions of the Lakes. A knowledge of the temperatures of the lake waters is essential for certain engineering projects.

Three steamship companies granted their co-operation: the Tree Line Navigation Co. Ltd., Canada Steamship Lines Ltd., and Canadian National Railway Steamers. The thermographs were installed by the chief engineers of the respective vessels, who changed the charts during the years of observation and provided abstracts of the ships' logs.

The observations came to an end during the war. After it, the abstracting of the results was completed under the direction of Mr. Andrew Thomson, O.B.E., present Controller of the Meteorological Division.

The findings of this paper consist of the monthly normals on arbitrarily divided short segments of the courses together with an examination of the standard deviations of individual readings from the normal for the day, the tendency of departures from normal to persist from day to day, and the standard deviations and probable errors of normals. The normals have been plotted as a function of time of year and location, and it is shown that the temperatures are closely related to the depth and current.

There is a pattern of the isotherms in a lake which is characteristic of the time of year. Summer and winter patterns differ because in the cold season the water

[1] Published by permission of the Controller, Meteorological Division, with which author was employed at the time the paper was written. The head office of the Meteorological Division is at 315 Bloor St. W., Toronto 5, Ontario.

[2] Author's present address: c/o Defence Research Board, Halifax, Nova Scotia.

J. Fish. Res. Bd. Can., 9 (7), 1952
Printed in Canada.

is near the temperature of maximum density, 39°F. Between 32° and 50°, the density changes little, so there is no development of stable density stratification, and vertical mixing takes place, with the result that surface isotherms tend to follow the depth contours. In summer the warm water is buoyant, and gathers in wide areas which are recognized as areas of convergence in the surface currents.

Lake Erie is relatively warm in summer because it is shallow and in the warmest climate of the Lakes region. Lake Superior is exceptionally cold because it is very deep and in the coldest climate.

THE INSTRUMENTS AND METHODS OF ABSTRACTING

Installations

In this survey of the temperatures of surface waters of the Great Lakes, temperatures were continuously recorded by thermographs installed on the condenser intakes of steamships. The courses traversed are shown in Figure 1, and the segments into which the courses were arbitrarily divided are also shown. The ships on these courses and the period of record are as follows:

Montreal to Fort William: *Willow Bay*—1935; *Weyburn*—1936 to 1941; *Saskatoon*—1937 to 1941.

Lake Ontario, Cobourg to Charlotte: *Ontario No. 1* and *Ontario No. 2*—similar installations used in turn, 1934 to 1946.

Detroit to Fort William and Duluth: *Hamonic*—1935 to 1940.

Depot Harbour to Milwaukee and Chicago: *Dalwarnic*—1936 to 1939, resumed 1941.

The thermographs were of the mercury-in-steel type, manufactured by Negretti and Zambra. The large bulb was installed in a copper sleeve let into the large diameter intake pipe of the steam condenser. In the *Willow Bay*, where only a few observations were secured before the ship was sold abroad, the intake was at a depth of 8 feet below the load waterline. In the other vessels the depth varied between 15 and 20 feet, not exceeding about 20 feet below the load waterline.

These thermographs were fitted with cylindrical clock drums. In the *Ontario No. 1* and *No. 2*, a 24-hour clock was fitted, but in the other ships 7-day clocks were supplied.

Calibration and Errors of Instruments

The thermographs were each calibrated at a series of points before installation. The sensitivity of the thermographs to a change in level of the bulb was checked, and was very slight. In tests aboard ship the thermograph bulb in the bucket was at a horizontal level near that of the site of installation in the intake, so no allowance for a change in level of the bulb was required. Immediately after installation a check at one temperature was made. Subsequently, at least once a season, a check was made at one or more points. A thermometer of certified accuracy was used for these tests, and corrections were applied where required. In these calibrations the thermograph bulb was withdrawn from the sleeve in the intake and placed in a large bucket of water which was stirred vigorously

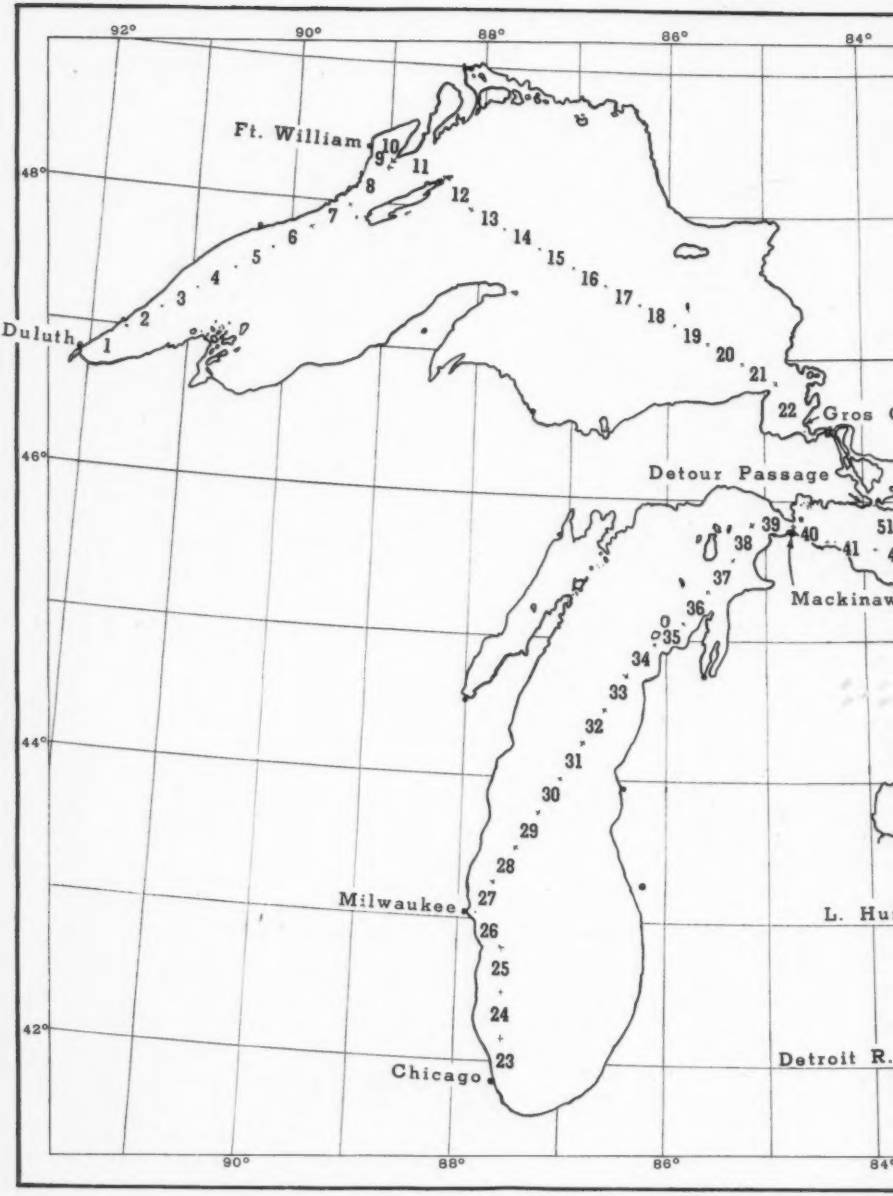
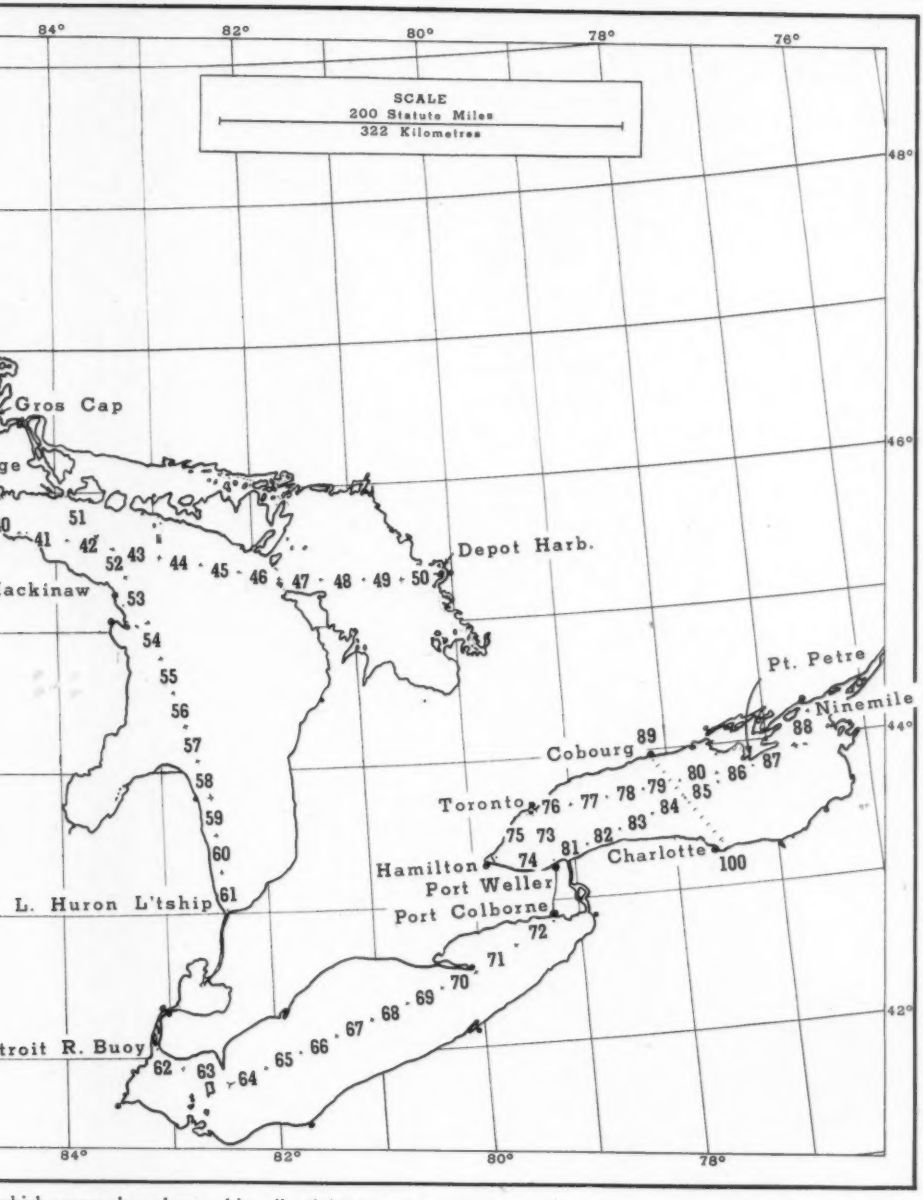


FIGURE 1. The numbered sections into which cou



which courses have been arbitrarily divided for averaging.

during the comparison. The thermographs responded with satisfactory rapidity, and the change of temperature of the water in the bucket during the test was allowed for by reading the check thermometer before and after reading the thermograph, and recording the average. Graphs of all calibrations were compared, and, where necessary, corrections were applied to the abstracts of the thermograph records. Zero adjustments were rarely made and were small except once when an instrument had been disturbed at a known time.

For any one thermograph, graphs of different calibrations ran parallel for the most part, showing a spread of about 0.3°F. above and below a mean curve. Subject to an allowance for a zero adjustment, the mean graph was adopted for a scale of corrections. A few calibrations showed a deviation of 1°F., and such deviations were not taken into account in the scale of corrections unless supported by other evidence. For instance, it was possible in a few cases to assume a temperature of 32°F. in harbour. In making abstracts, no attempt was made to apply corrections beyond those determined by the periodic tests. About 0.3°F. of the residual discrepancies is to be accounted for by a variation in the height of printing above the lower edge of the chart. Variations in humidity in the engine rooms were extreme, and would introduce further variations of a similar order because of expansion of the paper. Engineers were very good about seeing that the charts were down against the flange, but in a few instances it was found that the paper had been slightly above the flange. On the whole, residual instrumental errors of less than 0.5° are probable, and in view of the magnitude of random changes in the actual temperatures of the lake water, it is not worth while to try to reduce the residual errors further. Any systematic instrumental error is considered negligible.

Sampling Errors

Sampling errors may be of two types. First, the temperature of the water in the intake pipe may not be that of the water at the surface of the lake. Second, the geographical location corresponding to a segment of the record may not be correctly identified.

The temperature at the surface of the water in the lake will not necessarily be the same as that at the depth of the intake. To compare these temperatures, they were simultaneously observed on Lake Ontario from Cobourg, Ontario, to Charlotte, New York, on the night of October 16-17, 1934. The intake was at a depth of 13 feet. Results are presented in Figure 2. For any pair of simultaneous readings, a difference of 1°F. was observed in most cases, with an equal distribution of positive and negative signs. On the average the surface was cooler by 0.1°F. During the voyage the wind was Beaufort Force 2, and the wet bulb 48°F. In this case at least, the conclusion would be that random differences between the surface and the intake were of the order of 1°F., but that the systematic difference was negligible.

This experiment was carried out in the autumn season of convective overturn. Reference to further data will afford some support to the conclusion that a systematic difference is not large, even in the season of thermal stability.

Observations extending to a great depth have been made by Church (1942, 1945) in Lake Michigan, using the bathythermograph. These measurements showed a difference between the season of rapid cooling and the winter minimum on the one hand, and the late warming phase and maximum on the other. In the former category the temperature was fairly uniform right to the bottom. In the late warming phase, a condition typical of lakes in summer was reached. A relatively warm and practically isothermal surface layer, the epilimnion, floats upon the deep, cool water in the depths of the lake, the hypolimnion. The separating stratum with a steep thermal gradient is the thermocline. Church has presented four cases in June in which the epilimnion was not clearly developed as an isothermal layer. In these cases the temperature was about 3°F. lower at 15 feet depth, and continued to decrease until at 100 feet or more the temperature reached 39°F., and ceased to diminish below that. However, other observations in June showed the three regions well developed, and the temperature practically constant down to a level varying between 13 and 34 feet.

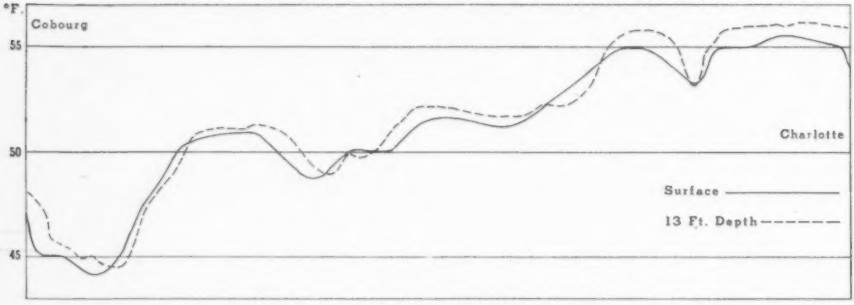


FIGURE 2. A test of concurrent observations of lake water temperature, by bucket sampling and at the condenser intake.

Examples in July showed an increase in the thickness of the epilimnion, and in August a further increase. Even with light winds the isothermal surface layer extended down to 30 or 35 feet almost everywhere in August, and to 50 or 65 feet after a wind of Beaufort Force 5.

H. B. Hachey (1950) has presented some bathythermograph observations in midsummer in Lakes Ontario, Huron and Superior. In Lake Ontario in mid-July, the bottom of the surface isothermal layer was in some cases only 7 to 10 feet from the surface, but mostly two or three times as deep. On Lake Huron, the only case illustrated was in keeping with observations by Church in Lake Michigan. On Lake Superior three types of sounding were encountered in late July: (*a*) isothermal, at 39°F., from the surface downward; (*b*) decreasing slowly from a surface temperature in the 40's to 39°, then isothermal below about 100 feet; (*c*) shallow isothermal surface layer in the 50's with a sharp discontinuity, of 3° to 5° at about 10 feet, followed by a slow decline to 39°, then isothermal below 100 feet.

The records of temperatures at condenser intakes indicate that in Lake Su-

perior patches of warm surface water a few miles wide are encountered here and there, becoming more closely spaced through July, until at the time of temperature maximum they are continuous in most areas. Between the warm areas the temperature is 39° or 40°F. Clearly, the surface isothermal layer has extended below the intake whenever warm water has been observed. At the season in question, the cases of doubtful type are those when 39° or 40° has been registered at the intake. In some of these the vertical temperature distribution would be as in soundings of types (*a*) or (*b*), when the intake temperature would satisfactorily represent the surface temperature. In others the distribution would be as in soundings of type (*c*), with the warm, isothermal, surface layer not reaching down to the intake. The relative frequency of the last occurrence is unknown, but one third is suggested as the maximum probability.

The conclusion to be drawn is that, for the major part of the year, intake temperatures are representative of surface temperatures; differences between intake and surface being of the order of 1°F., randomly distributed between positive and negative. On the other hand, in the late warming phase, there is a systematic tendency for the intake temperature to be lower than that of the surface. On Lake Superior this tendency has a maximum in late July, extending with lesser frequency from early July to the middle of August. On the other lakes this tendency is centred in late June, and extends with lesser frequency from mid-May to early August. It is estimated that the systematic error of the mean monthly temperature is less than 1°F. at the worst. Speaking of the difference as an "error" implies thinking of the intake temperatures as surface temperatures. There is no systematic error in the intake temperatures as such.

Errors due to incorrectly identifying the position of the ship at a moment of record are believed to have been negligibly frequent. The engineers provided an extract of the log, with the time of passing chosen landmarks. Because of inaccurate clock settings, the times provided by the engineers were not transferred directly to the charts. For each ship, the normal proportionate spacing of the landmarks was laid off on the edge of a card. The time of entering or leaving ports and rivers was readily identifiable by a change of temperature, and so the landmarks could be laid off with little chance of error. Chosen segments of the course were marked off at the same time.

Character of the Thermograph Tracings

A sample tracing is shown as Figure 3. The temperature was cleanly traced almost invariably, and an eye reading on a segment of the course was reproducible to 0.2°F. The lakes show a geographical variation in temperature at any instant of time, and gradients are most extreme in the season of rapid warming. Extremes more than 20° apart are possible, and changes of 10° may occur in a few miles. A discontinuity of 2° or more is normally to be noted when a ship passes a headland or shoal. The range and sharpness of the changes are reduced in the averages, as changes vary in strength and position.

Method of Abstracting

The steamship courses upon which the temperatures were regularly observed are illustrated in Figure 1. On some parts of the Lakes, the prescribed upbound

and downbound courses are separated by a few miles. No account has been taken of this, and the course on the map lies in the mean position. This figure also shows how the courses were arbitrarily divided into segments, mostly about 20 miles long. The length was adjusted to place divisions abreast of principal landmarks. The temperature was estimated by eye for each segment and tabulated on work sheets which have not been reproduced. Different ships were distinguished only for the application of instrumental corrections.

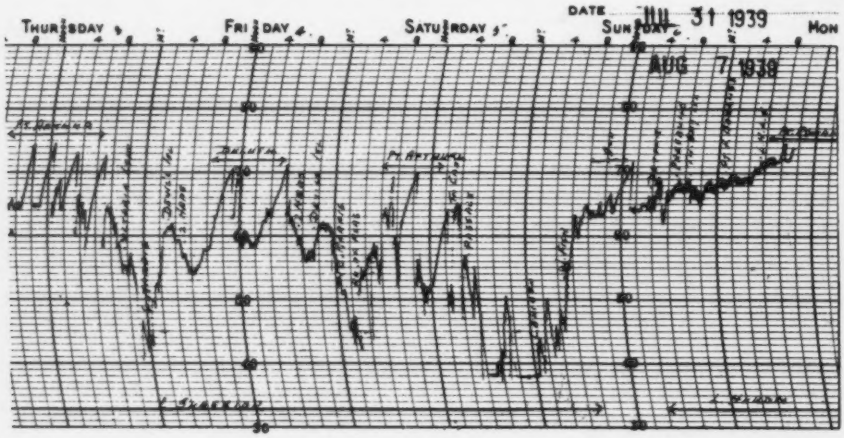


FIGURE 3. Sample record from thermogram installed on ship's condenser intake.

On most courses, at least two observations per week were obtained. Whenever two ships traversed a course on the same date, the results differed only by a fraction of a degree for the most part, and differences were mixed positive and negative. On Lake Ontario between Charlotte and Cobourg, two or three traverses a day were available, but no diurnal temperature cycle was superficially obvious. Changes over a few hours varied in sign along the course and were therefore assumed to be advective. It is certain that the diurnal range is small compared to the advective variability over a few hours. Accordingly, only one observation per day was abstracted on this course.

The original thermograms and the readings of temperature extracted individually from them have been microfilmed. The film is in two parts and is numbered G1. It is in the possession of the Controller of Meteorological Services, 315 Bloor St. West, Toronto 5.

THE DEPTHS OF THE GREAT LAKES

It will become abundantly evident that the surface temperature distribution in the Great Lakes is much influenced by the depth. Accordingly, Figure 4 is presented, showing the depths. At the times of the early warming phase or the late cooling phase, the temperature distribution in a lake is a blurred image of

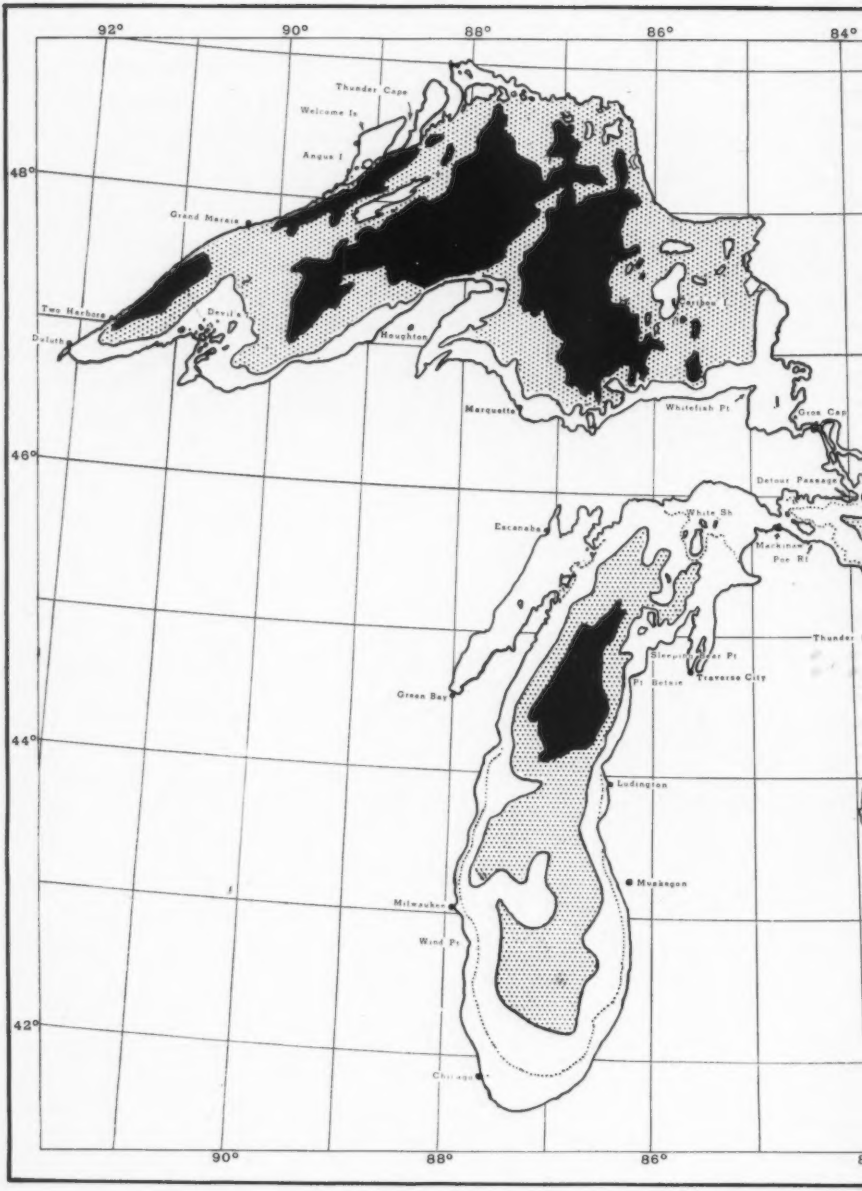
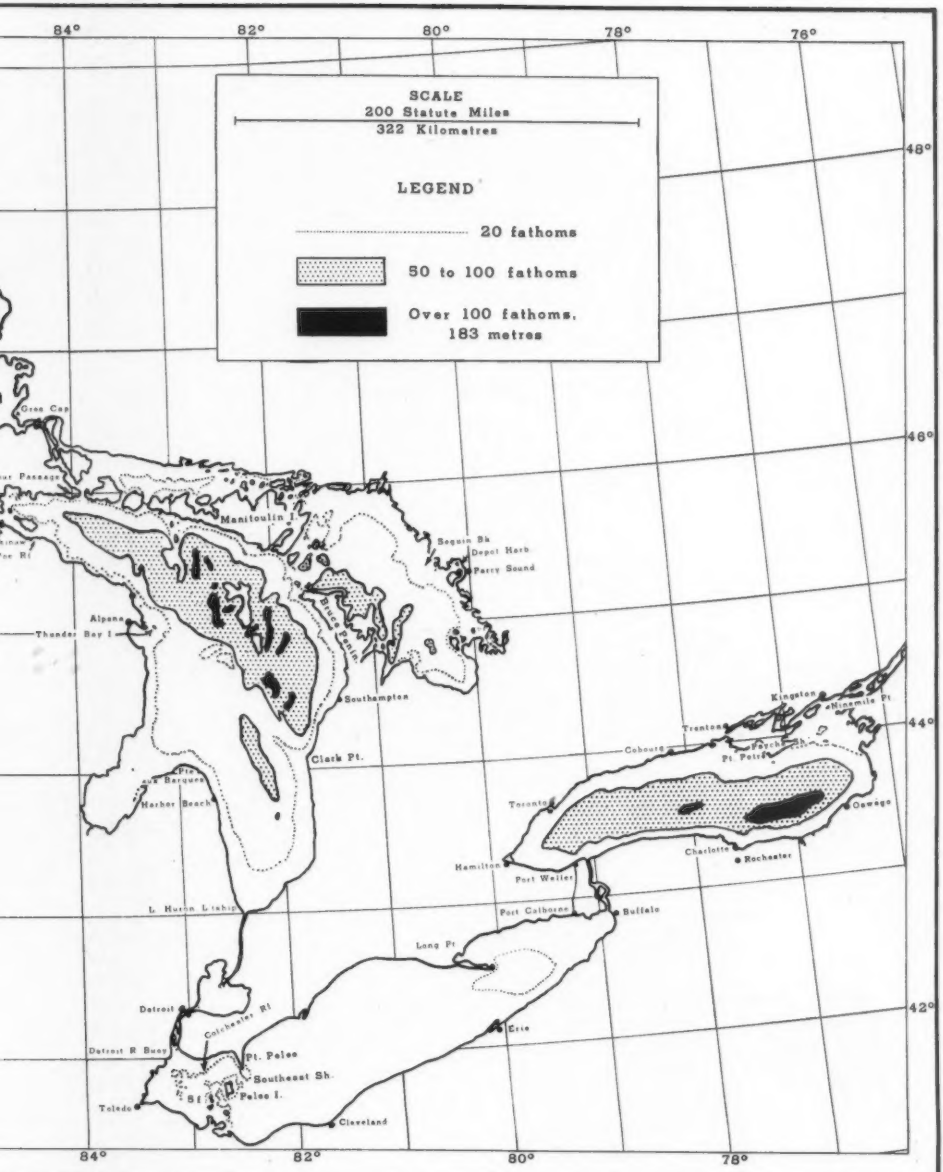


FIGURE 4. Depths



. Depths of the Great Lakes.

the depth distribution. In the figure, only the contours of 100, 50, and 20 fathoms have been drawn, except for a 5-fathom contour in western Lake Erie. These contours suffice to demonstrate the characteristics affecting the surface temperature. The outstanding features are the shallowness of Lake Erie and the great depth of Lake Superior.

The geology of the Great Lakes region is characterized by a zone of cuestas, like a flight of semi-circular steps facing north and centred on the State of Michigan. However, the strata forming the cuestas are centrally depressed in the form of a saucer. The Niagara Escarpment is the most prominent and best known cuesta of the series. It runs south of Lake Ontario, turns northwest at the west end of Lake Ontario, and swings in an arc through the Bruce Peninsula and Manitoulin Island in Lake Huron and through the ridge separating Green Bay from Lake Michigan. The cuestaform planes tilt upward towards the outer side of the arc. This accounts in some ways for the depth distribution, especially in Lakes Ontario and Huron.

In Lake Ontario the axis of maximum depth is well towards the south side. In Georgian Bay the deep area is concentrated to the west against the Bruce Peninsula. Green Bay on the northwest of Lake Michigan just reaches 20 fathoms, but it is comparable to the North Channel on the north side of Manitoulin Island in Lake Huron, where depths somewhat exceed 20 fathoms. These areas all lie at the foot of the Niagara Cuesta.

In Lake Huron a sublacustrine precipice extends from near Clark Point to near Detour Passage, and almost all the 50-fathom area lies northeast of this line.

In Lake Michigan there are three basins, but they are intimately connected, as the average depth of sections between the basins approaches 50 fathoms. In order from south to north, the basins might be described as deep, deeper, and very deep.

Lakes Erie and St. Clair lie on a plain smoothed over with drift and the deposits of a glacial lake. Lake Erie reaches a depth of 30 fathoms over only a small area east of Long Point. The extreme western end is mostly less than 5 fathoms, and St. Clair is everywhere less than 5 fathoms deep.

Lake Superior lies in the Precambrian rock, outside the arc of cuestas. In it there are two main very deep and broad basins, separated by an extension of the Keweenaw Peninsula. The shores of Lake Superior rise very steeply from the bottom. The 20-fathom line lies very close to shore almost everywhere, and along the north shore the same is true of the 50-fathom line. The isolated islands rise steeply from great depths.

CURRENTS IN THE GREAT LAKES

The distribution of temperature in the Great Lakes is connected with the currents. For example, the southeast side or end of every lake is relatively warm in summer, and this is attributed to the drift of warm surface water to these areas, under the influence of the prevailing westerly wind. Convergence and downsinking must occur in these areas. Compensating upwelling must occur else-

where, and is plainly evident in the temperature of certain areas to the west or north side of several lakes. An area of upwelling is relatively cold through the warming phase, and through the first half of the cooling phase as long as the floating mass of warm surface water has not yet been cooled to the temperature of the bottom water.

New observations of the currents of the Great Lakes are in progress, but at present the only published information is the bottle-drift statistics of Harrington (1895). The results are presented in Figure 5, redrafted from Harrington's charts. About one knot, more or less, is a typical strength for the most clearly marked currents. In general, the currents tend to circulate in cyclonic (anticlockwise) whirls in the broad and deep basins. As evidenced particularly in Lakes Michigan and Huron, the whirls tend to divide into approximately circular cells. The west-wind drift is identifiable in many areas, specifically along the axes of Lakes Ontario and Erie, across Huron and Michigan, and along the south side of Lake Superior. Harrington considered that the rotation of the earth would deflect the west-wind drift towards the south side of the lakes, but this is an over-simplification. A northward current along the east side, fed by the west-wind drift, is prominent in Lakes Huron, Michigan, and Superior. In these lakes this current continues across the north side or end. On the latter part of its course it is probably reinforced by a cyclonic motion associated with upwelling.

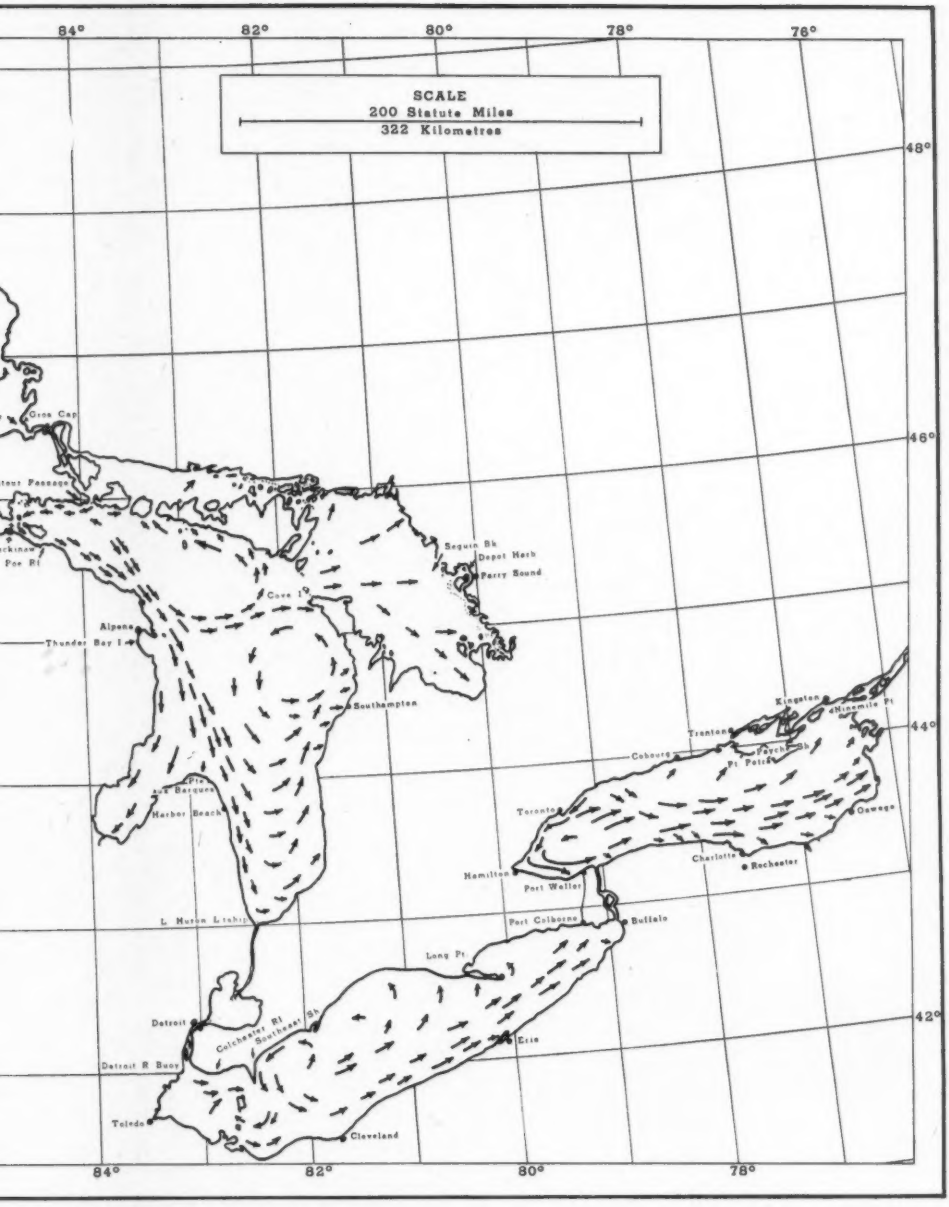
In Lake Ontario, a cyclonic whirl due to upwelling is present in the west end. Similar whirls are to be found in the north ends of Lakes Michigan and Huron, also associated with upwelling. In Lake Superior, a current setting south-southwest from Grand Marais is a continuation from the north-shore current, with reinforcement added by upwelling. Signs of cyclonic motion are least evident, though not absent, in Lake Erie, doubtless because bottom friction is more effective in this shallow lake.

The system of currents in Lake Erie discovered by Harrington has been confirmed by Olsen.

Harrington's drift observations were very consistent in direction. Few drifts deviated even a little from a single configuration of currents. Therefore the general system persists in spite of changing winds. Of course, temporary changes of current do exist, for example in connection with seiches. The varying patterns of surface-water isotherms, which have been observed in Lake Michigan by Church (1942, 1945), also suggest some changes in the currents. Nevertheless, it is clear that the general pattern persists with little change. Harrington's bottles were set adrift during the navigation season, and thus demonstrate the current system at an epoch of the year centred on the season of maximum temperature. However, no trend can be found in the original data suggesting different currents in May-June than in September-October.

It is hoped to present this result in another publication, but the mere statement will suffice here: about 10^{-6} part of the kinetic energy of the currents is destroyed per second by internal fluid friction and replaced by the work of the wind in driving the surface drift; there is a momentum effect which keeps the currents much the same in spite of day to day changes in the wind; 10^{6} seconds is 12

FIGURE 5. Chart of currents in the



ents in the Great Lakes, following Harrington.

days, a period long enough to orient the mean wind to the westerly. The prevailing wind remains near westerly all year, with only a moderate change in strength. It is generally accepted that winds are the principal cause of lake and ocean currents. It will therefore be assumed that the current systems persist much the same all the year and are caused by the westerly wind.

To a first approximation, currents obey the equation of the relative or density current (Sverdrup *et al.*, 1942, p. 422). In fresh water, the density current is a reflection of the temperature field only.

Notation: $2\omega \sin \phi$ = Coriolis acceleration

ρ = density

V = velocity

p = pressure

x = horizontal co-ordinate to right of V

z = vertical co-ordinate

$\frac{\delta\rho}{\delta z}$ = mean horizontal gradient of temperature down to depth Z, if possible to a depth where $V_z = 0$

Derivation:

$$2\omega \sin \phi \rho V = \frac{\delta p}{\delta x} \qquad \text{(Geostrophic current equation)}$$

$$2\omega \sin \phi \frac{\delta}{\delta z}(\rho V) = \frac{\delta}{\delta x}\left(\frac{\delta p}{\delta z}\right) = -g\frac{\delta \rho}{\delta x}$$

$$2\omega \sin \phi \ (\rho V - \rho_0 V_0) = -gZ\overline{\frac{\delta \rho}{\delta x}} = -gZ\overline{\frac{\delta \rho}{\delta T}\frac{\delta T}{\delta x}}$$

For a numerical example, suppose the current velocity is 0.5 m. sec^{-1} (1 knot), Z is 20 m. (10 fathoms), and the prevailing temperature is 60°F., giving $\frac{\delta \rho}{\delta T}$ as 9×10^{-5}. Then $\frac{\delta T}{\delta x}$ is 3° F. per km. (0.62 mi.).

The equation shows that a given velocity of surface current supports an increase in temperature to the right when $\frac{\delta \rho}{\delta T}$ is negative, which occurs above 39° F. Relatively warm shore water, or in winter cold shore water, are produced by the seasonal weather, and help to maintain the generally cyclonic currents. A strong gradient of temperature is favoured by a strong current, a small Z (shallow epilimnion), and by an average temperature near 39° F., making $\frac{\delta \rho}{\delta T}$ small. A density current is most likely to be detected by an anomaly in temperature during the warming phase, when these conditions are fulfilled. The anomaly will disappear in the cooling phase; for when cooling begins $\frac{\delta \rho}{\delta T}$ is large while the temperature is still high; then later Z increases eventually to the whole depth of the lake, because of the thermal overturn.

The strong currents on the east side of Lakes Michigan and Huron are identifiable by a local temperature maximum, which is strong in the warming phase.

The wind-drift current can be summed as a transport, mostly near the surface, in a direction approximately 45° clockwise from the surface wind. The transport should agree approximately with the vector mean of the surface currents over the lake as a whole. But there is no need for local agreement, so local currents can be much stronger than the theoretical wind drift, although the wind is their ultimate cause. Upwelling occurs to the west or northwest of a lake where the water rises to join the drift current, and downsinking to the east or southeast. Upwelling is equivalent to deep convergence and surface divergence, and downsinking to the reverse. As shown in the next paragraph, the areas of upwelling and downsinking can be identified by characteristics of the current system.

It is well known in meteorology and oceanography that horizontal convergence in the air or water creates cyclonic motion. The fluid participates in the rotation of the earth, and the effect arises from the conservation of angular momentum. Vorticity is a more general form of rotation than purely circular rotation, and is defined as $\frac{\delta V_y}{\delta x} - \frac{\delta V_x}{\delta y}$. Convergence in the horizontal plane intensifies positive or cyclonic vorticity and reduces anticyclonic; divergence does the opposite. If a streamlime becomes more cyclonically curved, or less anticyclonically curved, convergence is probably present. Convergence may also result when a current impinges on a coast, when streamlines converge in direction without a compensating increase in speed, or when the current crosses isotherms from high density to low.

The great cyclonic whirl in the south end of Lake Michigan results from surface convergence. The cyclonic whirl in the west end of Lake Ontario is from subsurface convergence of the bottom return current. The former example is associated with downsinking and a gathering of surface water, and the latter with upwelling.

If the current is purely a density current, it does not cross isotherms. The circulation theorem of V. Bjerknes shows that the current crossing isotherms implies convergence. The number of solenoids observable in a cross section is the vector product $\frac{1}{\rho^2}\,\text{grad}\,p \times \text{grad}\,\rho$ (Brunt, 1939, p. 181). In a horizontal section, this can be written $2\omega \sin\phi \,.\, V \,.\, \sin\chi \,.\, \frac{1}{\rho}\frac{\delta\rho}{\delta T}\frac{\delta T}{\delta x}$, where χ is the angle between the current and the isotherms, positive when the current is passing from high density to low. If the current is assumed steady and friction-free, the number of solenoids equals the rate of change of vorticity, which is $-2\omega \sin\phi \,.\, \text{div}\, V$. There is therefore a direct connection between convergence and the movement of the current from a high density area to low density.

When the current exists from a warm pool in summer, there is divergence. If the streamlines remain non-divergent in direction and do not become more anticyclonic, the current increases in speed as it leaves the area. This ejection of a

stream is exemplified in Lake Michigan near Muskegon. The northward current is partly caused by solenoidal acceleration.

In the study of surface temperatures, currents are to be used to aid in extrapolating the isotherms away from the area of observation. Currents should run approximately parallel to isotherms, with low density on the right. Where convergence is suspected, the currents should cross isotherms from high density to low, and where divergence they should cross the other way.

THE ANNUAL VARIATION OF MEAN TEMPERATURE

Data

The temperatures to be discussed here are the monthly means for the entire period of record set forth in Table I. Such means have been computed for each of the 100 segments into which the courses through the lakes have been arbitrarily divided (Figure 1). No number has been assigned to Lake St. Clair, nor to the course Milwaukee to Muskegon. Between the latter points data were obtained by reading off the diagrams in Church's papers (1942, 1945) and have been smoothed and used in the diagrams now presented, though not included in the table. Church's observations were made in only one season.

Table I. Monthly mean temperatures near the surface of the Great Lakes, in degrees Fahrenheit (see text for detailed explanation).

LAKE SUPERIOR MEANS

Duluth to Fort William, period of record 1935 to 1939.

Section	1	2	3	4	5	6	7	8	9
July	54.5	47.4	47.5	50.5	45.5	41.0	39.8	42.2	47.1
Aug.	62.5	60.0	58.6	59.5	58.1	55.4	54.5	55.6	57.1

Fort William to Gros Cap, period of record 1935 to 1939.

Section	10	11	12	13	14	15	16	17	18	19	20	21	22
May 16	37.0	35.3	35.2	35.1	35.0	35.2	35.0	34.8	34.8	34.7	34.7	34.9	36.8
June	45.9	41.1	37.4	37.1	37.1	37.2	36.9	36.8	36.9	36.9	37.5	41.0	44.9
July	54.4	46.3	42.6	39.4	39.1	40.7	38.8	38.4	39.8	40.4	41.3	47.3	54.3
Aug.	58.9	56.7	53.6	47.3	48.1	49.1	45.6	45.6	48.7	50.7	51.0	56.5	60.9
Sept.	54.2	52.7	51.7	49.9	49.5	49.4	48.6	49.6	50.7	50.6	51.7	54.8	57.4
Oct.	46.8	46.0	45.4	43.9	43.3	43.1	43.4	44.0	44.1	44.3	45.2	47.2	49.2
Nov. 15	40.8	41.0	40.8	40.3	40.2	40.3	40.3	40.5	40.7	40.9	41.5	42.5	43.5

LAKE MICHIGAN MEANS

Chicago to Milwaukee, period of record 1935 to 1941.

Section	23	24	25	26
May 22	50.8	45.0	41.3	43.5
June	59.1	54.8	52.7	54.2
July	69.5	68.5	66.8	68.5
Aug.	72.9	73.0	72.1	70.1
Sept.	67.7	67.7	67.1	65.8
Oct.	58.6	58.5	56.9	56.8
Nov. 13	46.6	47.0	45.5	44.9

TABLE I (*Continued*)

LAKE MICHIGAN MEANS—Cont'd

Milwaukee to Mackinaw, period of record 1935 to 1941.

Section	27	28	29	30	31	32	33	34	35	36	37	38	39
May 22	41.4	38.1	37.6	37.7	37.5	37.5	39.2	41.7	38.5	37.7	40.2	43.1	44.0
June	52.4	47.6	45.1	43.5	41.8	41.2	43.7	49.9	49.4	46.6	48.6	52.6	53.9
July	65.8	64.7	63.1	61.8	60.0	58.4	60.0	61.8	62.5	62.5	63.4	64.6	64.1
Aug.	70.0	70.1	69.0	67.8	67.0	65.2	66,3	66.7	67.4	67.7	67.8	67.6	66.9
Sept.	65.6	65.7	65.1	63.4	62.4	62.0	62.1	61.8	62.1	62.2	62.6	62.0	61.4
Oct.	54.0	54.3	54.2	54.0	53.4	53.2	53.1	53.1	53.6	54.3	54.9	54.2	53.2
Nov. 13	45.0	44.7	45.1	45.2	45.3	45.4	46.2	46.6	47.0	47.5	47.6	46.1	46.8

LAKE HURON MEANS

Mackinaw to Depot Harbour, period of record 1935 to 1941.

Section	40	41	42	43	44	45	46	47	48	49	50
May 22	42.4	39.4	35.6	35.5	35.6	35.3	36.0	38.1	35.4	36.4	40.6
June	53.3	49.7	44.2	40.7	41.4	39.6	42.6	47.6	41.6	44.6	52.2
July	64.6	64.3	61.8	59.7	59.3	56.9	59.1	60.4	61.6	61.8	65.5
Aug.	70.1	66.1	66.1	65.7	64.8	64.7	65.2	65.7	66.9	67.8	69.1
Sept.	60.6	60.4	59.9	59.8	59.4	59.7	59.8	60.5	60.8	61.4	62.3
Oct.	51.5	50.4	50.1	49.7	49.9	50.4	51.4	51.5	52.0	52.7	52.9
Nov. 13	44.0	43.4	43.4	43.6	44.7	45.7	46.0	45.7	45.9	46.6	45.5

Detour to Lake Huron Lightship, period of record 1935 to 1941

Section	51	52	53	54	55	56	57	58	59	60	61
May 16	40.2	36.1	36.7	37.5	37.0	37.2	37.6	38.7	39.6	41.1	43.3
June	50.6	45.1	46.3	47.9	47.0	46.7	47.9	49.2	50.7	51.5	52.7
July	62.7	60.8	60.9	61.6	62.0	62.7	64.0	65.4	65.9	66.4	67.1
Aug.	65.2	64.9	65.8	66.2	66.4	67.2	66.2	68.4	69.2	69.2	69.9
Sept.	59.3	58.1	58.8	59.6	60.5	61.3	62.1	63.0	63.8	64.3	64.8
Oct.	49.1	49.8	50.9	51.4	52.1	53.1	53.6	54.2	54.7	55.7	56.4
Nov. 15	42.4	42.9	43.0	43.3	44.1	44.9	45.6	45.9	46.1	46.3	46.8

LAKE ERIE MEANS

Detroit River to Port Colborne, period of record 1937 to 1941.

Section	62	63	64	65	66	67	68	69	70	71	72
April 27	43.9	39.8	38.4	38.0	38.6	39.3	39.9	37.8	35.3	35.3	35.8
May 19	56.6	54.9	50.9	48.3	47.6	47.9	48.5	48.8	47.9	45.2	45.7
June	64.6	65.2	64.0	61.9	61.4	61.2	61.2	61.2	60.9	60.6	60.7
July	72.1	72.7	70.8	69.7	69.5	69.1	69.3	68.9	68.4	67.8	68.6
Aug.	73.4	74.1	74.2	74.0	74.1	74.0	73.4	72.9	72.7	72.1	72.2
Sept.	65.4	67.7	67.9	68.2	68.1	68.1	68.2	67.9	67.2	66.8	67.3
Oct.	53.7	57.7	59.1	60.3	60.2	60.0	59.9	59.4	58.7	58.7	58.6
Nov. 15	45.2	46.3	49.3	50.6	51.0	50.9	50.4	49.9	50.1	51.0	50.4

TABLE I (*Continued*)

LAKE ONTARIO MEANS

Port Weller, via Hamilton and Toronto, to 20 miles west of Point Petre, period of record 1937 to 1939, only a few observations.

Section	73	74	75	76	77	78	79	80
May 20	—	47.5	41.3	40.0	37.6	37.1	36.9	37.7
June	—	57.1	55.8	55.9	53.3	52.7	54.9	53.5
July	—	68.7	68.6	64.9	67.5	68.1	67.0	66.7
Aug.	—	72.7	69.4	68.2	66.6	69.6	70.1	70.3
Sept.	—	66.2	64.8	65.8	65.9	66.9	67.7	67.4
Oct.	—	57.8	57.0	56.7	57.4	57.6	57.6	57.2
Nov. 10	—	41.1	40.5	42.0	43.2	43.9	46.3	47.8

Port Weller to Ninemile Point, period of record 1936 to 1941.

Section	81	82	83	84	85	86	87	88
April 25	39.7	35.8	35.5	35.3	35.3	35.3	35.9	36.3
May	48.3	41.6	36.8	36.5	37.6	40.2	42.8	44.7
June	56.8	54.6	51.2	49.9	48.4	49.3	50.7	52.5
July	68.6	68.2	67.4	67.4	66.8	66.3	67.2	67.4
Aug.	68.5	68.4	69.3	69.3	68.9	68.8	68.5	69.6
Sept.	64.8	64.3	65.2	63.5	63.4	63.4	64.0	64.9
Oct.	54.8	53.8	54.0	53.9	54.4	54.7	55.0	56.0
Nov. 7	45.5	46.9	47.0	48.1	49.0	48.3	47.9	47.4

Cobourg to Charlotte, period of record 1937 to 1946.

Section	89	90	91	92	93	94	95	96	97	98	99	100
Jan.	34.3	35.5	36.6	37.7	38.5	39.1	39.3	39.3	39.0	37.8	36.3	35.3
Feb.	33.9	34.5	35.0	35.5	35.8	36.2	36.5	36.5	36.3	35.6	34.7	34.2
Mar.	35.1	35.1	35.2	35.1	35.0	35.1	35.3	35.4	35.6	35.4	35.1	35.2
April	38.9	37.1	36.6	36.3	36.3	36.3	36.4	36.4	36.4	36.6	37.3	38.7
May	45.9	42.7	40.6	39.4	38.6	38.3	38.4	38.5	38.7	39.9	43.5	46.5
June	52.8	53.4	54.1	53.4	52.1	50.7	49.5	49.4	50.8	53.8	57.9	59.9
July	61.4	63.0	64.5	65.3	66.0	66.4	66.7	67.1	67.8	68.7	69.7	70.9
Aug.	66.6	68.2	68.9	69.3	69.7	70.3	70.6	70.9	71.0	71.1	71.0	71.8
Sept.	61.8	62.5	62.9	63.5	64.2	64.7	65.0	65.0	65.1	65.3	65.4	65.7
Oct.	53.9	54.4	53.9	54.5	55.0	55.4	55.7	55.9	56.0	56.1	55.9	55.7
Nov.	44.5	45.3	45.7	46.1	46.7	47.1	47.1	47.2	47.2	47.0	44.6	45.8
Dec.	36.7	38.9	40.3	40.9	41.5	42.0	42.2	42.2	42.0	41.1	39.3	37.0

The means in the table approach the true normals within a certain probable error, which is to be discussed. Means were obtained without any adjustment for the distribution of observing dates within the months, but in the table the mean date has been given where it was appreciably off the centre of the month.

PRESENTATION

In Figures 6 to 15 the relationship of temperature is shown with respect to two variables, location and time. This has been accomplished on a single diagram by making one axis distance along the course, and the other axis time. Separate sheets have been taken for each principal section of the courses, lake by lake. On

working sheets the monthly mean temperature was entered in the middle of the square for each segment and month, then contours drawn in. Only the contours have been reproduced. The contours represent the shape of a curved surface in space, drawn through points located above the surface of the paper at a distance equal to the temperature. A plane perpendicular to the paper and parallel to the time axis will intersect the temperature surface so as to give a profile of the temperature through the year at any chosen place. A plane perpendicular to the paper and parallel to the distance axis will intersect the temperature surface so as to give a profile of the temperature along the course at any chosen time of year. The contours have been drawn by proportional parts and have required very little smoothing adjustment. It will be evident that local details extending through less than a segment will be obscured, and so will features that vary their position in less than a month. However, suppression of temporary or local detail brings out the broad and persistent features.

Maps of the mean monthly surface temperatures of the lakes have also been drawn. Inevitably, the run of isotherms away from the courses of the observing ships is conjectural. In drawing the isotherms, consideration of the effects of currents gives a coherent interpretation and minimizes uncertainties in placing the isotherms.

The order of presentation is from the Lower Lakes upward, because more data is available from Lake Ontario, including winter temperatures, and points noted may be looked for on the other lakes. Lake Superior presents unique features.

Lake Ontario

The Charlotte-Cobourg course was the one on which the most observations were obtained, over the longest period of years. Mean results are shown in Figure 6.

In this diagram it has been possible to trace a centre line denoting the end of the cooling phase and the beginning of the warming phase. The water near shore reaches its minimum temperature, about 34°, early in February, but the water in midlake does not reach its minimum of 35° until almost the middle of March. In this interval the shore temperature has risen 1°. The reason for the early minimum near shore is that the temperature there has early reached an equilibrium between cooling from the air and warming by exchange mixing with midlake waters. The midlake waters have a lag in phase because of their great thermal capacity. Church (1942) has shown, for Lake Michigan and presumably for all the Great Lakes, that the temperature is uniform from the surface to the bottom in the late cooling phase and at the winter minimum. Thus the thermal capacity of the whole depth is effective.

Similarly, a centre line has been traced for the axis of the maximum temperature, which lies entirely in the month of August. This is not much distorted, but the peak temperature is reached slightly earlier on the south side. This is in keeping with several indications that south-side water has had a longer history as surface water than north-side water. Upwelling occurs on the north side.

From the winter low and through the early warming phase, temperatures have a minimum, and through the cooling phase a (slight) maximum, in a zone some-

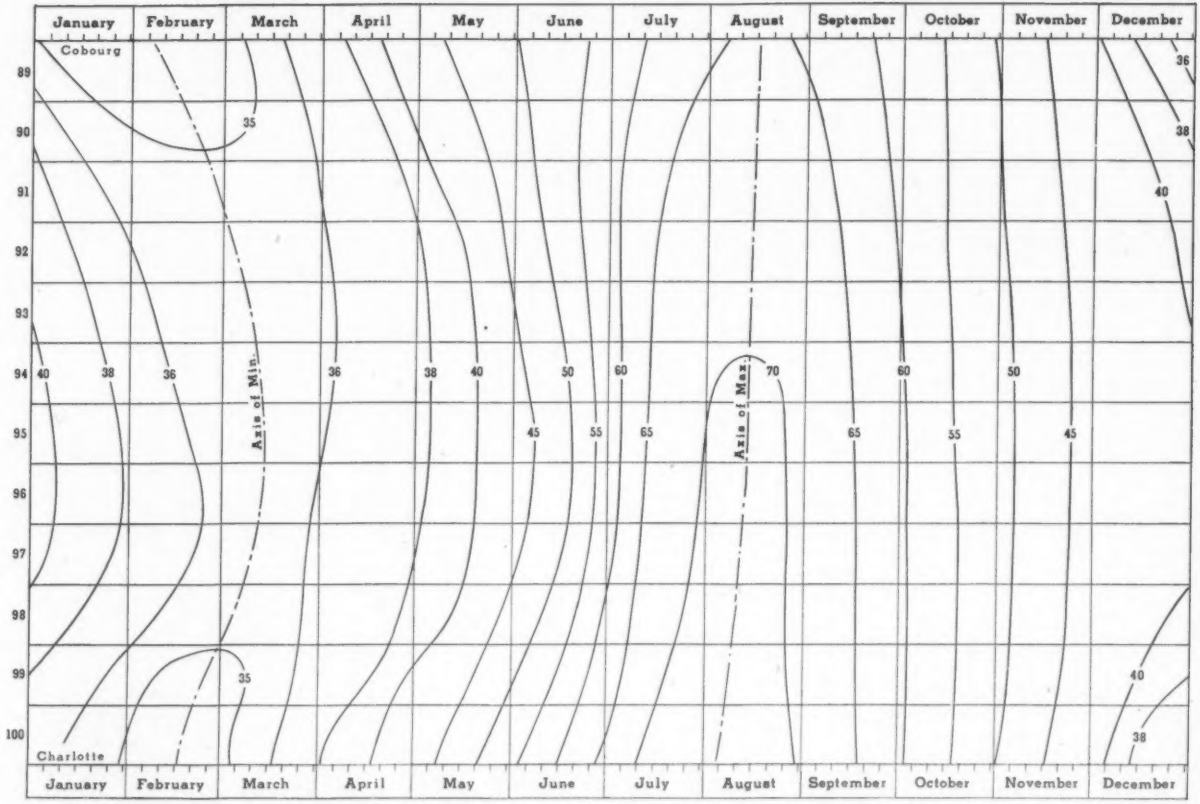


FIGURE 6. Annual march of temperature in Lake Ontario between Cobourg and Charlotte, averaged 1937 to 1946.

what south of midlake. This zone corresponds to the area of depths exceeding 80 fathoms (150 metres). This indicates the dominating influence of depth on the surface temperatures, in seasons of unstable or only slightly stable density distribution. On the other hand, in the late warming phase and at the summer high, the maximum is displaced to the south shore. This indicates a strong control by stability, so that the influence of great depth is not appreciable at the surface.

At the north shore, from mid-June to the end of August, the temperature is so low relatively that upwelling is demonstrated. Upwelling is also consistently present off Toronto in the same season. The rather narrow band of cold is well known to ships' engineers, as it affects the operation of the condenser. Chilly bathing is regularly encountered on beaches at and near Toronto, and has been notorious at times of record high air temperatures. All evidence indicates persistent upwelling in a narrow band from Hamilton to somewhere east of Cobourg. This upwelling is associated with the season of general density stability. Thus, at this season, such overturning as exists is distributed in persistent areas of upwelling and downsinking. Through the remainder of the year, overturning is broadly distributed as deep turbulence, both frictional and convective.

Church (1942) was able to draw a synoptic map of the surface temperatures of Lake Michigan for the period March 30 to April 4, 1942. In this case the area of minimum temperature was distributed in an offshore zone, with slightly higher temperatures both inshore and in midlake. Examination of the individual thermograms between Charlotte and Cobourg has disclosed that the same phenomenon is present in some of the observations in March and April. Early in this period, the water may show a rise of two or three degrees in the last mile towards shore. Later, a rather flat minimum may be found 5 to 10 miles offshore, with only a slight and broad maximum in midlake. On individual thermograms the variations along the midlake section are in the form of step-like discontinuities of 1° or less, of a transient nature. This is suggestive of variable currents, with waters of different history in contact at the discontinuities.

In April and May, the temperatures in midlake show a broad flat at 39°, which is a very persistent characteristic. Beginning near shore a zone of thermal gradient develops, and widens until in early June the two zones meet in midlake. The zones of gradient are quite variable in form, temporarily showing steps, minima, and sharp discontinuities. In many cases the gradient is concentrated mostly into one large discontinuity or a band of steep change a few miles wide. Such steep gradients tend to be farther toward midlake and to become less steep as the season advances toward the late warming phase. Any such discontinuity or steep gradient is suggestive of the boundary between water masses which had a different recent trajectory. Large-scale mixing can be seen at work.

The orientation of the course from northwest to southeast, in spite of slight obliquity, is favourable for deducing the current along the axis of the lake by considering it to be a density current. In a frictionless density current, the mean isopycnals (isotherms) are parallel to the current. In the portion of the density field which is established by the wind-drift current, the mean isotherms are rotated a few degrees counterclockwise from the direction of the surface wind and surface

drift, but the angle is negligible in a qualitative consideration. In general, the temperature field along a cross section can be taken as indicating the component of current normal to the section.

During May, June and July, the temperature minimum in midlake is a density maximum. During the winter, the temperature minimum in midlake is again a density maximum, since water has its maximum density at 39°. This distribution of temperature is attributable to the distribution of depth. The distribution of density must give rise, both in summer and winter, to a density current eastward near the south shore and westward near the north shore. Near the south shore the temperature gradient is a little narrower and steeper than near the north shore, suggesting a net eastward transport in surface layers of the cross section.

During May, June and July, there is a strong evidence of upwelling near the north shore, and water to the south would have a longer surface history and possess a deeper epilimnion of warm water. Logically, the epilimnion must increase in thickness from north to south. This would add an eastward vector to the density current all along the course, and produce a net surface transport eastward.

In August the surface temperature is uniformly increasing and the density uniformly decreasing from Cobourg to Charlotte. Again, the warm layer must increase in depth from south to north. Thus the density current is uniformly setting eastward, with increasing intensity from north to south.

The tendency of the south side to be warmer than the north persists in the autumn cooling phase, but is very weakly shown. This is because the autumn convective overturn increases the thickness of the layer involved in the overturn, eventually to the full depth of the lake. A very small horizontal gradient of density is then required to balance the current system.

The work of the wind in driving the wind-drift current is in the long run equilibrated by the expenditure of energy in fluid friction. In the season of little density contrast, potential energy cannot be stored temporarily in a density distribution, with which density currents are associated. It is inferred that a net eastward transport exists in the surface waters at all seasons. The strength and persistence of the eastward wind drift is amply proved by Harrington's bottle drifts. This current is attributable to the stress of the prevailing westerly wind. The returning current must be subsurface. This necessitates downsinking in the east end of the lake and upwelling in the west. The resultant distribution of currents over the lake as a whole is to receive further examination after review of temperature observations along the east-west axis of the lake.

Interpretations such as in the preceding paragraphs can be made upon the observations on courses lengthwise of Lake Ontario. Although these observations were inferior in frequency and length of record, the more pronounced geographical trends of the temperature repeated themselves from year to year. Reasonable agreement of the means was noted where the courses crossed the Cobourg to Charlotte line. Where the temperatures did not agree at intersections, reference to the original records showed that too few observations were available on the

lengthwise courses, and the discrepancy was due to sampling error. Weight was therefore placed on the Cobourg to Charlotte readings.

On the course from Port Weller to Ninemile Point, as shown in Figure 7, the most striking feature is the uniformity of temperature at the times of the late warming phase, the summer maximum and the early cooling phase. Isotherms on the surface of the lake should therefore run approximately parallel to this course, although not necessarily so when all surface gradients were small. The density currents across this line would therefore not be appreciable. This does not rule out the possibility of a net surface transport eastward due to the wind drift current, crossing the course at an acute angle.

Along the middle one-third of the course between Port Weller and Point Petre, the depth exceeds 80 fathoms (150 m.). In May and June, the resistance of this section to the spring warm-up is notable, and the somewhat slower cooling in autumn, relative to the rest of the course, is detectable. This is the trough of maximum depth, for which the same remark has been made in reviewing the Cobourg-Charlotte course. The rapidity of the spring warm-up relative to the autumn cool-down, is pronounced, and is attributable to stable stratification of the water in spring, in contrast to unstable in autumn.

The course from Port Weller to Ninemile Point via Hamilton and Toronto is shown in Figure 8. No results are depicted east of a point 20 miles west of Point Petre, as the observations to the east were combined with those of the direct course. The notable features were the August maxima between Port Weller and Hamilton, and west of Point Petre. These are two areas of depth less than 40 fathoms (750 metres), which appear to be areas of surface convergence. In the west end, the known current setting south impinges on the south shore and is deflected to the east, and surface convergence is implied.

Point Petre is the south point of the peninsula of Prince Edward County. As may be seen on a large scale map, bars across bays on the west side of the peninsula point northward, and a northward-setting current is implied. Harrington's experiments showed bottle courses turning northeast to the west and south of the peninsula, swinging from a straight line into cyclonic curvature. Surface convergence west of the peninsula is indicated. The area of surface convergence must be bounded on the northwest before Cobourg is reached, because of the upwelling along the north shore.

The prevailing westerly winds, producing a persistent wind drift, must produce surface convergence in the east end, to a greater extent than in the areas just mentioned. The westerlies are strengthened by the east-west lie of the lake, and super-gradient winds have often been observed by means of an anemometer installed on S.S. *Ontario No. 1*. A strong westerly drift to the east end of the lake has been confirmed by Harrington's bottle-drift experiments. Since high temperatures elsewhere in August have been shown to be associated with surface convergence, a broad area of high temperature in the east end is inferred. Some observations of temperatures by S.S. *Ontario No. 1* near Oswego confirm this, but have been too few in number to be presented as averages.

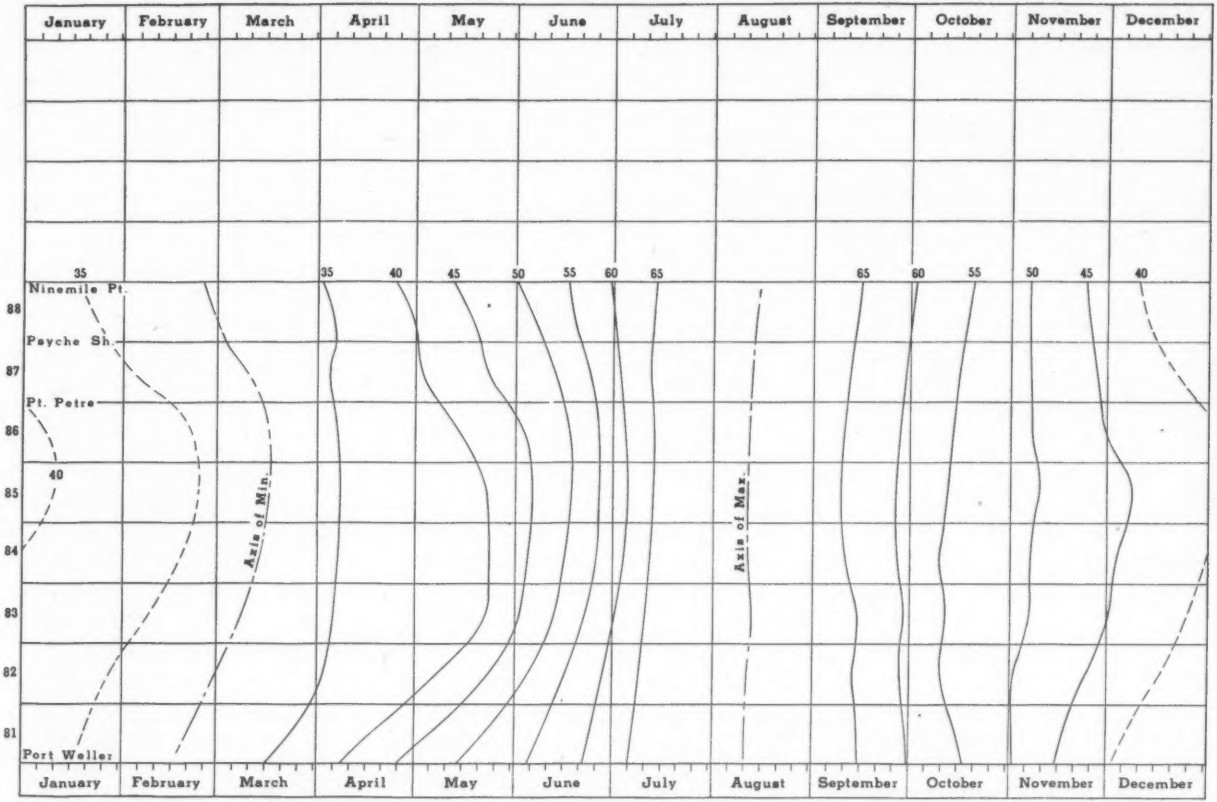


FIGURE 7. Annual march of temperature in Lake Ontario between Port Weller and Ninemile Point, averaged 1936 to 1941.

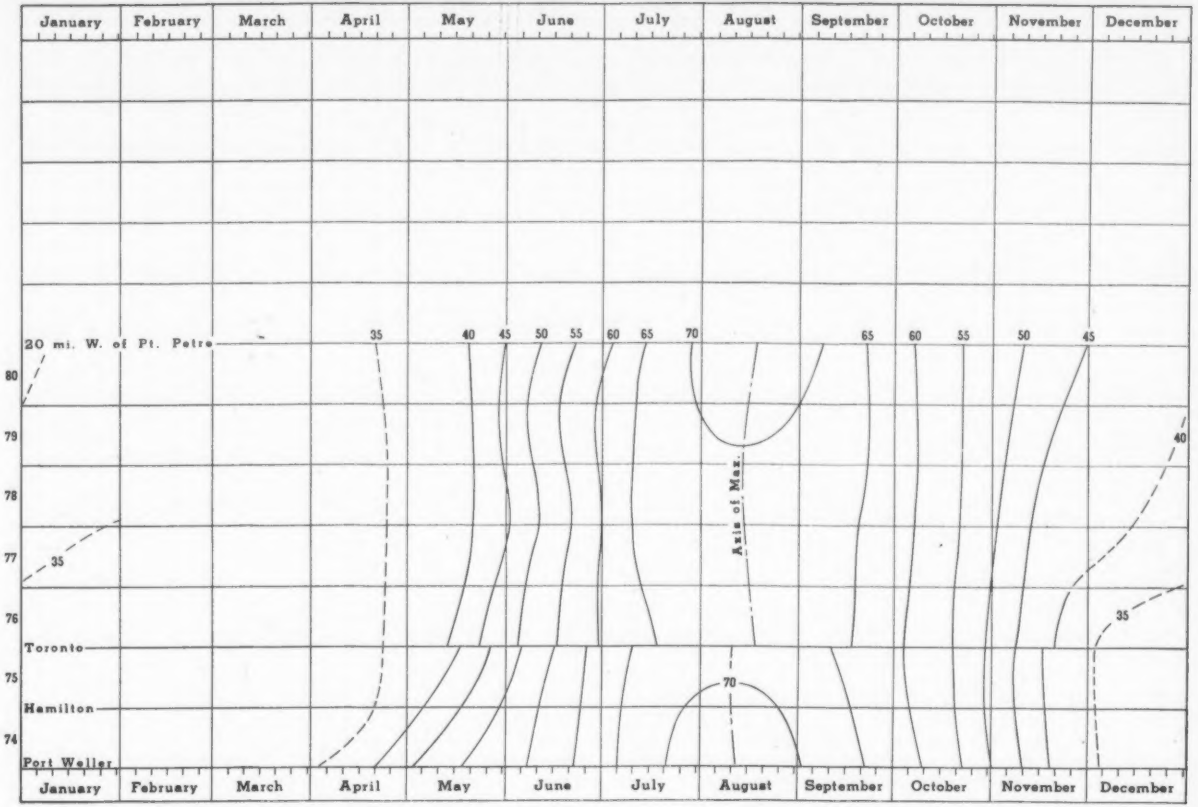


FIGURE 8. Annual march of temperature in Lake Ontario along the course from Port Weller via Hamilton to Toronto, thence to a point 20 miles west of Point Petre; averaged 1936 to 1939.

Isotherm maps of the monthly mean surface temperatures of Lake Ontario have been constructed, and are shown in Figures 16 to 27. On the courses where temperatures have been observed, the temperatures are known, but away from the courses the run of isotherms has had to be inferred. It has been possible to trace logical isotherms on the basis of the observed temperatures alone, and it is encouraging that they agree excellently with inferences based on the physics of currents. It is only in the southeast quarter of the lake that extrapolations become relatively free.

In April, the 37.5° isotherm follows the 35-fathom (64 m.) contour in the west end of the lake, with shore water warmer, up to about 39°. However, near Point Petre and eastward, the 37.5° isotherm approaches closer to shore than elsewhere. This would be because, in this part of the lake, the wind-drift current would drive the cold midlake water closer inshore. The centre of the lake is occupied by an area of temperatures of 36° to 37°, bounded approximately by the 60-fathom (110 m.) line.

In May, the gradients become steeper, so more closely spaced contours are to be drawn. An oval area of minimum temperature, of about 36.5 at the lowest, probably exists west of the Cobourg-Charlotte line. Shore temperatures exceed 46°—with 48° off the mouth of the Niagara River the highest. For reasons soon to be discussed, this high is attributed to local convergence rather than to the efflux of the river. With the support of the observations, the isotherms are traced to show colder shore water near the northwest area of upwelling, and warmer water with widely spaced isotherms in the east-end convergence area.

In June the oval centre of minimum temperatures, down to 47.7°, is found displaced to the east of the Cobourg-Charlotte line. This effect is believed to be real, not a result of statistical error, because it is consistent with the transition from the May to the July configuration. The curves in the isotherms near the north shore are based on uniformity of temperature in the first three segments of the course out of Cobourg, and in the following month a stronger curvature is called for. The midlake minimum exists because of the possibility of easy mixing to full depth while thermal stability is slight. Above 48°, thermal stability increases rapidly, so it is no surprise to find that this minimum has disappeared by the next month. Its displacement eastward in June would be due to the eastward wind-drift current.

In July the trend of the isotherms has changed greatly. The general pattern is of isotherms running from west-southwest to east-northeast, with the warm less dense water to the southeast. Hence the topography of the surface rises to the southeast. The eastward wind drift crosses the isotherms at an angle, ascending to a higher level of gravitational potential. The wind-drift current is doing work, resulting in a storing of potential energy, its distribution being reflected in the topography of the water surface and the density distribution through the body of water. This energy is injected by the forced subsidence of warm water in areas of surface convergence, disturbing the stratification of warm water over cold. The disturbed stratification possesses gravitational potential energy, which is recoverable as kinetic energy.

The convergence of water in the east end of the lake causes subsidence there. The returning subsurface current curves anticyclonically towards the north shore, and upwelling results there. Owing to subsurface convergence in the area of upwelling, the flow there has cyclonic vorticity, and a cyclonic current results around the west end. A bend in the isotherms northeast of the Niagara river suggests an accumulation of warm water off the Niagara shore.

The cyclonic current in the west end is not directly wind-driven. From the time it leaves the principal area of upwelling near the north shore until it approaches Port Weller, it is crossing isotherms from low temperature to high, and is ascending to a higher gravitation level. The current in this stretch is giving up kinetic energy obtained elsewhere, and supplying potential energy to the density distribution. This forces the ponding-up of warm water against the Niagara shore, and locally adds to the potential energy of the density distribution. Some subsidence must result there. East of the Niagara River, the current is crossing isotherms from high to low temperature. So, in the exit from the western eddy, the current acquires some energy from the density distribution, and is therefore a narrow and rapid stream against the south shore.

To sum up the condition for July, it is found that a large area of warm water occurs to the southeast, where it is ponded up by the wind-drift current. A smaller warm area occurs off the Niagara shore, where it is ponded up by the west-end cyclonic whirl.

In August the accumulation of warm water to the southeast has become broader with little gradient inside it. The accumulation of warm water and of potential energy has reached a maximum. These facts would suggest a density current from Port Weller to Point Petre. West of Point Petre there is some indication of a warm area, which would be due to ponding-up by this current.

The warm area off the Niagara shore is in August concentrated in the end of the lake west of Port Weller, and has become resistant to the further storing of potential energy. The isotherms are parallel to the cyclonic current, which is therefore doing no work. The accumulation of potential energy is at a maximum there.

August is therefore characterized by a maximal development of ponds of warm water, with signs that currents are ceasing to do work in the storing of potential energy.

In September, temperatures have begun to drop all over the lake. Upwelling of cold water continues along the north shore, and its identification by temperature as cold water from the depths will not disappear until November. The prominent 65° isotherm runs parallel to the wind-drift current except in the west end, so no potential energy is being added to the main warm pool in the east end. However, the cyclonic current in the west end still maintains the warm pool on the Niagara shore without intensifying it.

In October the gradients of temperature have become flatter, and it has been difficult to draw isotherms. Reference has been made to the scanty data of individual years along the lengthwise courses, and it has been seen that the following are the significant features of the temperature distribution. Cold upwelling still exists near Cobourg, a large warm area in the east end, and a small warm area on

the Niagara shore. Mean isotherms have been traced accordingly, giving much weight to the long record between Cobourg and Charlotte. The pattern resembles the September one.

In November the pattern has changed to a type heavily controlled by depth. With surface temperatures of 48° and lower, the whole lake is relatively labile in spite of temperature variations. Even prior to this month, convective mixing must have occurred because of surface cooling. In view of the pronounced change which has set in, the convection did not previously extend to the bottom, but now does. To a first approximation the isotherms follow the bottom contours, and the area of maximum temperature is found over the deep trough. However, the centre of warm water is displaced towards the east end because of the wind drift. The warm area on the Niagara shore has disappeared.

In December the data are scanty except between Cobourg and Charlotte, but the available information shows that the isotherms follow the bottom contours.

It is supposed that all through the winter, isotherms parallel the bottom contours. In the early winter the spacing is probably proportional to the change in depth, but this ceases to be true in the early warming phase.

The whole cycle of the year has now been examined for Lake Ontario, and this concludes the study of mean temperature distribution over the surface of this lake.

Lake Erie

The only available course on Lake Erie was from Port Weller to Detroit River Buoy, with about five observations (total for several years) per month during the season of navigation. Except for Lake St. Clair, Lake Erie is the shallowest lake, possessing a central depth of only 13 fathoms (24 m.). However, there is a deep of 34 fathoms centred eight miles east of the tip of Long Point. An oval 20-fathom contour surrounding the deep is about 40 miles long from east to west and 20 miles wide from north to south (60 x 30 km.). The west end behind the islands is very shallow. The course from Southeast Shoal to Colchester Reef traverses the deepest part of this bay, which even there is only 6 fathoms (11 m.) deep.

The largest island, Pelee Island, is the most southerly part of Canada. Except for the Pacific coast, Pelee Island and the neighbouring main shore are the warmest part of Canada. The run of air temperature through the year is similar to that of coastal Massachussetts or the extreme southern end of Lake Michigan.

Through the season of observation, May to November, Lake Erie is the warmest large lake. The variation of mean temperature along the course through the year is to be seen in Figure 9. In May the deep east of Long Point is the coldest part at 46°F., but only the warmest part of Lake Ontario, near the Niagara shore is equally warm. In this month a typical midlake temperature for Lake Erie is 48°, but for Lake Ontario only 39°.

Speaking of monthly averages, the summer maximum reaches 74° over much of Lake Erie, 71° for Lake Ontario. The maximum is reached earliest in the shallow western bay. As for individual observations, the highest recorded temperatures anywhere on the Lakes were 81°, between Detroit River Buoy and Southeast Shoal, on August 10, 1938, and 81.5° in Lake St. Clair on the same day. On that

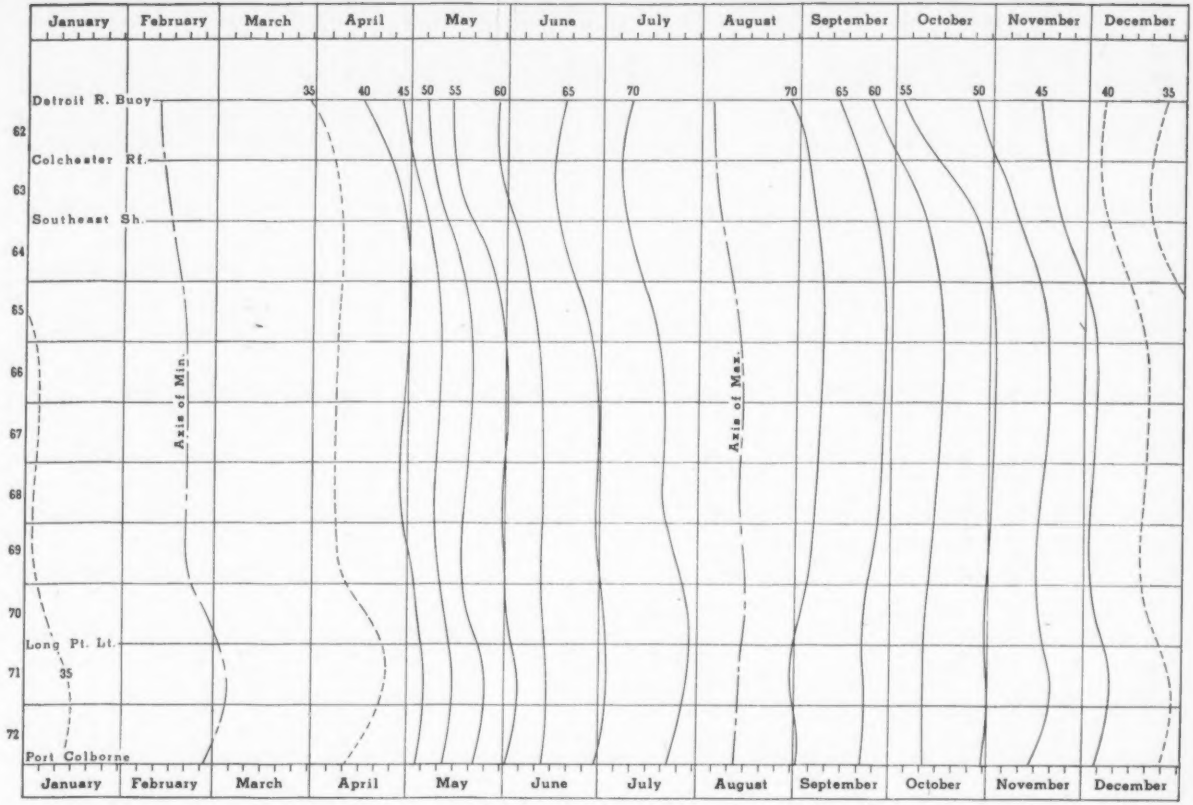


FIGURE 9. Annual march of temperature in Lake Erie between Detroit River Buoy and Port Colborne, averaged 1935 to 1941.

date, the average of the traverse from Detroit River Buoy to Port Colborne was 77.0°. By comparison on Lake Ontario on August 8, the highest temperature was 75.2° off Charlotte, and the mean of a traverse from Cobourg to Charlotte was 73.0°. Also on August 10, 1938, in Lake Michigan, the highest temperature was 75° between Chicago and Milwaukee, and the average between these ports was 72°. On the same day Lake Superior displayed, as usual, its great contrast to the other lakes, and temperatures down to 39.2° were observed in midlake; the average between the Welcome Islands and Gros Cap was 51°.

In November, Lake Erie is still the warmest of the large lakes. Between Detroit River Buoy and Port Colborne the average is 49°, compared to 47° for Lake Ontario between Cobourg and Charlotte.

Lake Erie may not remain the warmest lake in winter. When ice forms, areas of the western Bay normally freeze fast for the winter. The lake as a whole is thinly iced over sometimes for a period of days only. It remains mostly clear in midlake, as do all the Great Lakes except St. Clair. Field ice gathers in the east end and governs the time navigation opens in the spring through the Welland Canal.

The spring warming is remarkably rapid in the shallow and enclosed west end. Otherwise, the rates of spring warming and autumn cooling are approximately the same as the rates in Lake Ontario and in Lake Michigan-Huron. It is remarkable that the rates of warming and cooling of Lake Erie do not differ greatly from those of the medium-deep lakes. There is more difference in these rates within a single lake than between different lakes taken as a whole. The explanation seems to be that an epilimnion forms over these lakes, isolating the deep water with its large thermal capacity.

Lake Superior is different; as the water remains near 39°F. little density stratification is possible and there is little epilimnion formation.

The distribution of temperature on the surface of Lake Erie month by month is now to be discussed, with reference to Figures 16 to 27.

Because of the shallowness, the warm centre east of Long Point may go as low as 33 in winter. In the absence of observations until late in April, it is assumed that the temperature rise in this month will be less than in the later months, and by mid-April the area east of Long Point, now a minimum, may not have risen quite to 35°. At the same time, shore waters have probably risen above 39°, higher than in Lake Ontario. Actual observations in Lake Erie in late April were made on four voyages only, but they show that by the end of the month temperatures rise to about 45° between the Detroit River and Colchester Reef; to 40° in midlake, and 36° from Long Point to Port Colborne.

In May Lake Erie has already reached a temperature that other lakes will reach in June. An area of 45° remains in the deep between Long Point and Port Colborne. Most of the midlake area is enclosed in the 50° isotherm, and the western bay is up to 55°. This distribution remains the same in June, but the whole surface temperature is up 10°. In July, the shape of isotherms remains the same, but the gradients are reduced. In August more than half the lake, to the west end, is at 74°, but the deeper eastern end has not reached so high a maximum.

During the season of navigation at any rate, temperatures near Port Colborne are never as high as in the west end of the lake. This is especially worthy of remark during the late warming phase, as it indicates an absence of ponding-up of warm water at the east end of the lake, such as is found in Lake Ontario. This may be partly because the axis of Lake Erie is rotated about 30° counterclockwise compared to Lake Ontario, so that the prevailing westerlies drive the surface water to the south shore. Harrington has observed that currents in Lake Erie are generally weaker than in the other Great Lakes, except for short periods over limited areas in spring and autumn. This verifies the existence of greater friction. It is probable that in this shallow lake the forces of bottom and internal friction modify the vorticity more than in the other lakes. Therefore less evidence of ponding-up due to the conservation of vorticity is to be seen in the temperature distribution. The temperatures in midsummer should be more closely related to depth than in the deep lakes, and this helps to explain why the deeper east end of Lake Erie remains colder.

If ponding-up of warm water occurs anywhere in Lake Erie, it is in the western end. Harrington's observations of current can be interpreted to indicate a ponding-up south of a line between Cleveland and Southeast Shoal, which is dynamically similar to the ponding-up in Lake Ontario along the Niagara shore. Whereas the current in Lake Ontario swings around the extreme west end, the corresponding current in Lake Erie is diverted by the shoreline to a southeasterly direction from Southeast Shoal, and divides about 20 miles (30 km.) from this landmark, part turning south and west to the islands. Upwelling is suggested from Southeast Shoal to the dividing of the current, but ponding-up is probable along the south shore, especially where the current makes the passages between the islands but stops there.

This current arises from the upwelling of return water from the wind-drift. Ponding-up results from the impact of the current against the south shore. Consequently it is possible for this current to impound warm water during the warming phase, and cool water during the cooling phase.

Ponding-up of warm water along the south shore west of Cleveland is well indicated by the July isotherms in the area. Mean temperatures of the water observed at the Cleveland waterworks intake crib have been available, and justify the assumed trend of the isotherms. The ponding-up in the southern arc of Lake Erie accounts for the exit of the main current from the west end through Pelee Passage, the most northerly channel. This current is the stream of the Detroit River, and this is the only lake in which the inflow water can be identified by its temperature. From the beginning of June onward, the water near the inlet is slightly cooler than from Colchester to Southeast Shoal. The current passes along the north side of the western bay, which is the deepest, and the water over the extensive shallows to the west and south of the bay is subject to little motion. This accounts for the rapid heating and high maximum temperature in these shallows, together with a closed centre of slightly lower temperatures to the northerly side of the bay.

During the cooling phase, relatively cool water is impounded in the western

bay, and as far east as Cleveland is contained by the current against the south shore.

In September the whole of Lake Erie has a temperature near 68°, but the area slightly above 68° is enclosed by a contour coinciding approximately with the contour of 10 fathoms' (18 m.) depth. The temperature is below 66° between Detroit River Buoy and Colchester Reef, and it is assumed that all sheltered water less than 5 fathoms deep has a temperature below 66°.

In October temperatures are down 8° over the open lake, and down 11° over the shallows, as compared to September. In November they are down about 10° more. In November the extension of the 45° isotherm towards Cleveland is based on a waterworks intake temperature of 46° at that city. No observations were available in December, but an estimate of the distribution of mean temperature can be extrapolated. Probable values of the monthly mean are 36° in the western bay and 42° over much of the midlake area.

Surveys of the surface water temperature on a number of occasions in eastern Lake Erie have been published by Parmenter (1929). Gradients of temperature are naturally stronger than in mean maps. The distributions of temperature observed are in general agreement with those now presented, and fill in some good detail.

Lake Erie is notable for its high temperatures even in the autumn. Evidence of upwelling is found only in the currents, not in the distribution of mean surface temperature. Considering the shallow depth, this must indicate that there is little temperature contrast between surface and deep water.

Lake St. Clair

No results are presented for Lake St. Clair because it is small, possessing only 0.5 per cent of the water surface of all the Great Lakes, and also because of the difficulty of reading the temperature on the thermograph records. The temperature usually changed several degrees from inlet to outlet. A ship passed through in less than two hours, and it was not easy to identify the exact time of entering and leaving the lake. As weekly charts were used, readings could not be extracted accurately.

The maximum depth is 3 fathoms (6 m.), and the temperature cycle is closely similar to the farthest west segment of Lake Erie.

Lake Michigan

Observations of temperature at a ship's condenser intake were available on Lake Michigan from Chicago via Milwaukee to the Strait of Mackinaw. The observations made by Church (1942, 1945), with the bathythermograph, complement these observations with data secured on a different set of courses.

From Chicago to the Strait of Mackinaw via Milwaukee, two observations with the intake thermograph were regularly available each week during the season of navigation. The period of record was from 1935 to 1939 plus May to July 1941. From Chicago to Milwaukee the course lies inside the 20-fathom line. From Milwaukee to Point Betsie the course is almost all upon depths of more than 50

fathoms, and over more than 100 fathoms in the last forty miles towards Point Betsie. North of Sleeping Bear Point, the course passes behind islands over depths of more than 50 fathoms for some distance, in a basin occluded from the main body of the lake by 20-fathom shoals. It is only for about four miles south of White Shoal that any real shallows are approached.

Church has published diagrams for thiry-three temperature cross-sections between Milwaukee and Muskegon, observed between November 22, 1941 and September 13, 1942. This number of observations justifies comparing them with the condenser intake observations. Surface values have been read from Church's diagrams, smoothed, and incorporated in the diagrams now being discussed. Church's observations on other courses will be taken into account in a general way only, by adopting a run of mean surface isotherms over the lake as a whole which will agree approximately with Church's synoptic maps in the season to which they belong.

The course from Milwaukee to Muskegon coincides with the boundary between the middle and south basins of Lake Michigan. This course is 80 miles long. The first 20 miles east from Milwaukee are over the western channel, and the next 20 fathoms are over depths of approximately 40 fathoms, including the Milwaukee Reef which rises to 32 fathoms. The next 20 miles are over the uniform slope of the west side of the east channel. This channel reaches a maximum depth of 60 fathoms about 20 miles west of Muskegon. The last 20 miles toward Muskegon contain a discontinuous upslope; the eastern wall of the channel is locally precipitous, rising from 59 to 29 fathoms at a distance of 8 miles from Muskegon.

According to Harrington's observations of the currents, all surface drifts in Lake Michigan feed a heavy, northward-setting current along the east side. The south basin is occupied by a powerful cyclonic whirl. It is fed by a broad, southward current bringing water from the west side of the middle basin, through the west channel centred about 15 miles off Milwaukee. In turn this whirl feeds the great, east-side current through the east channel off Muskegon. Church's observations of temperatures in the depths show that these currents are deep, and have their axes 10 miles more or less from the shore.

North of the dividing section between Milwaukee and Muskegon, the lake does not form isolated cyclonic whirls. Except for the current diverted past Milwaukee to the south basin, all drifts cross the lake and add to the strength of the east-side current.

The annual cycle of surface water temperature in Lake Michigan is shown in three sections, south, east, and north of Milwaukee. The first of these, from Milwaukee to Chicago, is shown in the lower part of Figure 10. This course runs close to shore, and near the terminals the temperatures may be of rather local significance. However, the 20 miles south of Wind Point have approximately the same annual cycle as the middle of the section from Milwaukee to Muskegon, and so probably represent the midlake condition. Presumably the temperature near Chicago would be the same as a strip near shore around the south end of the lake.

The upper part of Figure 10 shows the cycle of surface water temperature between Milwaukee and Muskegon. The period of these observations, November

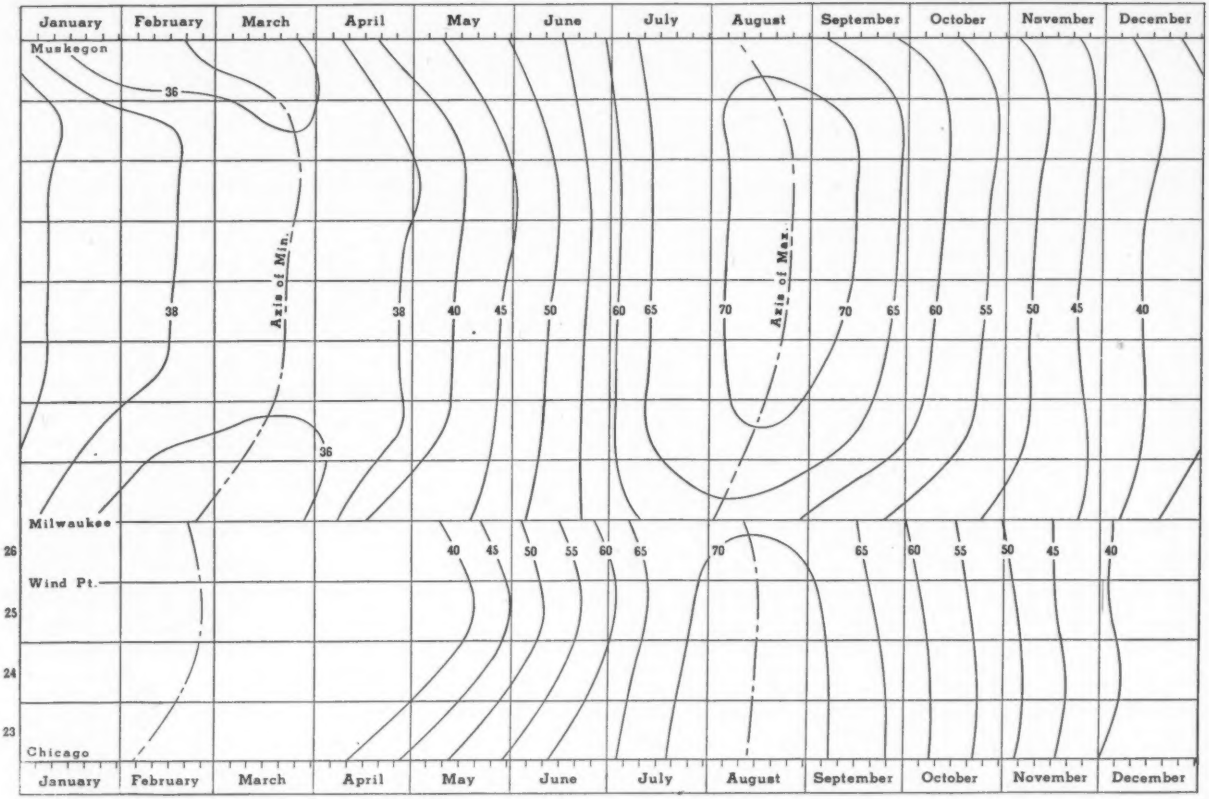


FIGURE 10. Annual march of temperature in Lake Michigan; upper section Milwaukee to Muskegon, season of 1941-1942; lower section Chicago to Milwaukee averaged 1935 to 1945.

22, 1941 to September 13, 1942, was near normal as to air temperature, except that April was 6.7° F. above normal at Chicago. Church (1945, Table I, pp. 90-91) has given the mean surface water temperature between Milwaukee and Muskegon, and these have been plotted against the dates (diagram not reproduced). Smoothing the curve over April and May suggests that the water surface temperature was 0.5° F. above normal in April and 0.2° F. above in May. These anomalies have been subtracted from values used in preparing the diagram. The autumn 1941 air temperature was also above normal, the highest anomaly being 4.2° F. in December at Chicago. However, the amount of anomaly in the water temperature was not evident, so no adjustment has been made in the autumn values. On account of the short period of record, agreement is not expected at Milwaukee between these temperatures and the averages of condenser intake temperatures.

Through most of the year, the water is colder near Milwaukee than farther offshore. In winter this is attributable to cold shore water, accumulated from farther north. This explanation seems to be verified by the localized warmth here in April and May, which seems to be warm shore water. On the other hand, it is relatively cold here in midsummer, and more so in autumn; this suggests upwelling. Such upwelling would indeed be expected on account of the west-wind drift. It has been noted that localized upwelling is most evident at high summer, but continues into autumn. It is a dynamic result of the impounding and subsidence of warm water elsewhere. Since the warm area in the south end of Lake Michigan is so extensive, without doubt the upwelling near Milwaukee continues into autumn.

Near Muskegon, as compared to midlake, the early warming in spring and early cooling in autumn result from a current trajectory near shore around the southern bay. In late April the lowest temperatures are about a quarter of the lake width out from Milwaukee or Muskegon. Church has drawn a synoptic map, showing that these minima are the intersections of a belt of minimum paralleling the shore. The minimum occurs because the central deep water never becomes as cold in winter as the shore water, but then the shore water warms up more quickly, leaving a belt of minimum between. As shown by the cross section, a belt of maximum occurs in autumn in the same way.

Figure 11 presents the results between Milwaukee and White Shoal (20 mi. or 33 km. west of Mackinaw). The outstanding feature is the warm spot during the warming phase between Point Betsie and Sleeping Bear Point. This is where the course intersects the northward current of the east shore. Although the thermal evidence of the current disappears in autumn, this does not imply that the current ceases. This is the best example of a known current demonstrated in the temperatures. To explain why the temperature reveals the current only in the warming phase, recourse is had to the density current equation, for which the symbols were defined in the section on the theory of currents:

$$\rho V = -\frac{gZ}{2\omega \sin \phi} \overline{\frac{\delta \rho}{\delta T} \cdot \frac{\delta T}{\delta x}}$$

$\frac{\delta \rho}{\delta T}$ is small when the temperature is near 39°, so $\frac{\delta T}{\delta x}$ will then be large, other

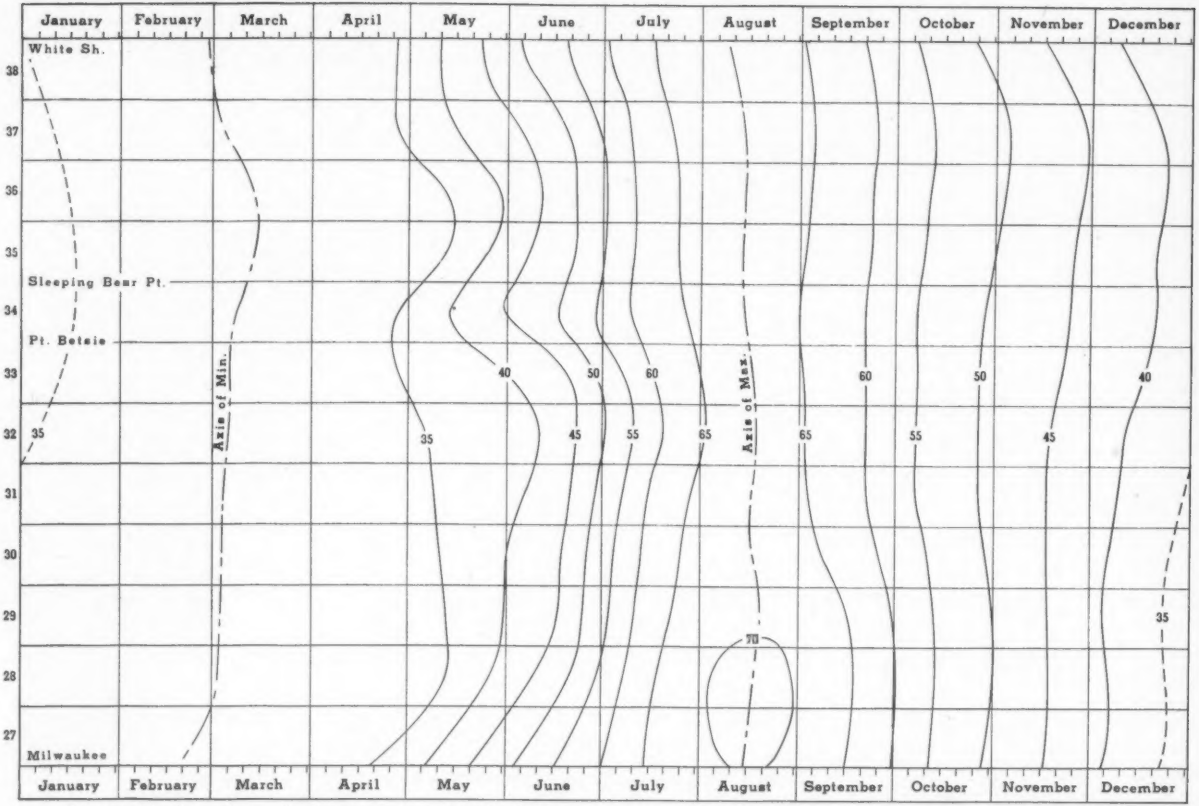


FIGURE 11. Annual march of temperature in Lake Michigan between Milwaukee and White Shoal, averaged 1935 to 1941.

things being equal. Z is practically the thickness of the epilimnion, which is relatively shallow until late in the warming phase, making $\frac{\delta T}{\delta x}$ large. Z becomes great as the midsummer maximum temperature is approached, and later as the thermal overturn sets in, increases to the full depth of the lake. The effect of the northward current is to confine warm water against the shore. Considering the terms in the equation, the thermal contrast is strong only in the warming phase.

Part of the current enters the deep northwestern bay behind the islands. In April, May and June the current has little depth and volume, and therefore in spite of its relatively high temperature, the bay remains as cold in its deep part as the open lake. From July to December the current may not be noticeable for its high temperature, but its depth and volume is then great. Its heat content is considerable, for the bay remains warmer through the entire cooling phase than the open lake southeast of Point Betsie.

The higher temperature near Milwaukee, for most of the season of observation, marks where the course enters the fringe of the warm area in the south end of the lake.

The distribution of surface temperature in Lake Michigan is now to be discussed month by month, with reference to Figures 16 to 27. For the first four months the only information available is Church's. It is very likely true that isotherms run parallel to the shores.

In May, the first signs show of the impounding of warm water in the south end. In the northeast, an almost closed cold centre is drawn around the deep behind the islands. To account for a warm belt west of the islands, it is supposed that some of the east-shore current passes to west of the islands; also that some relatively warm water is brought to the region of the islands by the cyclonic current from the north shore.

In June there is little change in the shape of isotherms. Most of the lake has warmed up ten degrees since May, except in the middle of the north basin where the warming has been as little as 4° F. Over this broad, deep basin, warming is slow, as in Lake Superior. Between Ludington and Sleeping Bear Point, there are close isotherms paralleling the shore, thus strongly indicating the prevailing current.

The July configuration is transitional to the August. In August, the 70- and 72-degree isotherms bend southward on the east and west sides, quite a different shape from the previous month. The form of isotherms is significant in the distribution of work done by currents, as will emerge in later paragraphs.

The pond of warm water in the south end arises principally from the transport of surface water southward by the wind-drift current. As mentioned in the section on the theory of currents, the drift caused by the prevailing westerly wind has a southward component. The south end, although deep, is less deep than the north end, which also tends to increase the temperature southward. As currents move into the south end, the cyclonic curvature of streamlines increases, as shown by

Harrington. All signs point to strong convergence and downsinking, especially in the centre of the whirl.

In compensation, the north end must possess broadly spread upwelling which, along with the great depth, explains the lower temperatures of the north end.

In September the gradient of temperature between the north and south ends of the lake becomes arranged as parallel isotherms running southwest to northeast, in the direction Milwaukee to Ludington. Looking back to the earlier months a tendency to this alignment is foreshadowed, and looking forward to October it is found more strongly developed.

By reference to the currents, it is apparent that from May to October the current southeast of Milwaukee crosses isotherms from low temperature to high. And along the east shore it crosses isotherms from high temperature to low. The Bjerknes circulation theorem has been touched upon in the section on the theory of currents, and leads to the following deductions.

Southeast of Milwaukee there is convergence, and the solenoids of the density distribution are retarding the current; but as the current is maintained the current must be intensifying the concentration of solenoids. This can be seen in another way, for the warm water of the southern whirl, having a relatively greater specific volume than cold water elsewhere, is heaped up. (It is to be understood that the slope of the free surface and other isobaric surfaces is too slight to be easily detected—only about one part in a million.) The current is ascending the slope against gravity, the energy of the work being derived from the wind and being converted into potential energy in the density distribution. Conversely, the current leaving the east side is impelled by gravity in its descent, thus extracting energy from the density distribution.

It is now to be noted that in the area near Milwaukee the work per unit area diminishes as the season advances, because the isotherms swing counterclockwise making an ever-smaller angle to the current. On the other hand, near Muskegon the isotherms remain more nearly perpendicular to the current and the work done upon the current is maintained. Early in the season, net work is done by the current to build up the pond of warm water, but late in the season the density distribution is doing work to maintain the current system. The dissipation of the potential energy of the pond is visible in the spread of warm water northward along the east shore.

By November, the entire east shore to the extreme north has received the warm water. From Wind Point northward on the west, the water remains relatively cold, and water in the area may be identified as upwelling bottom water. The temperature of the upwelling water is about 45° F. (7° C). According to the observations of Church (1942) the temperature of the west side of the lake near Milwaukee is very close to this value down to a depth of about 30 fathoms (55 m.). This water consists of warm surface and cold bottom water which have been mixed over a period of many weeks, leaving only a small residue of maximum density water at the bottom. In the uniform layer down to 30 fathoms vertical mixing can easily take place, and seeing that the lake is warmer elsewhere, upwelling is considered to be present.

There were not enough observations in December to warrant striking averages. By comparison with Lake Ontario it may be inferred that isotherms would run approximately parallel to the shore.

Lake Huron and Georgian Bay

Observations on Lake Huron were available firstly along the west, and secondly along the north shore, the latter course continuing eastward across the middle of Georgian Bay.

Currents in Lake Huron resemble those in Lake Michigan. The temperature conditions as well as the currents suggest ponding-up of warm water in the south in summer, with convergence and downsinking, compensated by upwelling and a cold cyclonic whirl in the north end. As in Lake Michigan, the generally greater depths in the north end and lesser depths in the south contribute to the temperature contrast between the ends.

The course along the west shore coincides closely with a southward belt of current, originating to the north in deep water with upwelling, and proceeding to shallower water with convergence and downsinking to the south. The course across the north end is far enough offshore to pass over the centres of cyclonic whirls which possess broadly spread upwelling. The cyclonic motion originates in convergence in the subsurface current returning from the south end.

The information about currents in Georgian Bay is slight. Cyclonic motion does not seem to occur, but the surface drift drives the warm surface water to the east or southeast. In addition, the relatively shallow depth to the east and southeast increases the relative warmth.

Figure 12 shows the distribution of temperature through the year along the west shore of Lake Huron. The outstanding feature is that the north end is the colder at all times including the cooling phase. This proves that the warm surface water migrates to the south end. By extrapolation to late December, it seems that the warmest area then is section 57, north of Harbor Beach, Michigan. According to the currents, this area possesses upwelling, and may also receive occasional surface currents from the deep water to the northwest. The cooling would therefore lag. This warm area is analogous to the area in Lake Michigan in November, where warm upwelling prevails off the western shore.

Figure 13 shows the distribution of temperature through the year in the Strait of Mackinaw, across the north end of Lake Huron, and across Georgian Bay. The most noticeable peculiarity is the warm spot near Cove Island in the warming phase. Warm water is received by mixing from nearby shores where the water is warmer, while the current in Lake Huron favours the retention of stray warm masses near Cove Island. The dominating current is the eastward current from near Alpena, Michigan. This current increases its cyclonic curvature west of Cove Island, suggesting convergence. Low density, high temperature water should gather there. Some of the warm water may reach the area from the southeast along the west shore of Lake Huron.

Some sign of a warm spot during the warming phase shows on Figure 13 near Great Duck Island. On individual thermograms, a narrow maximum occurs here

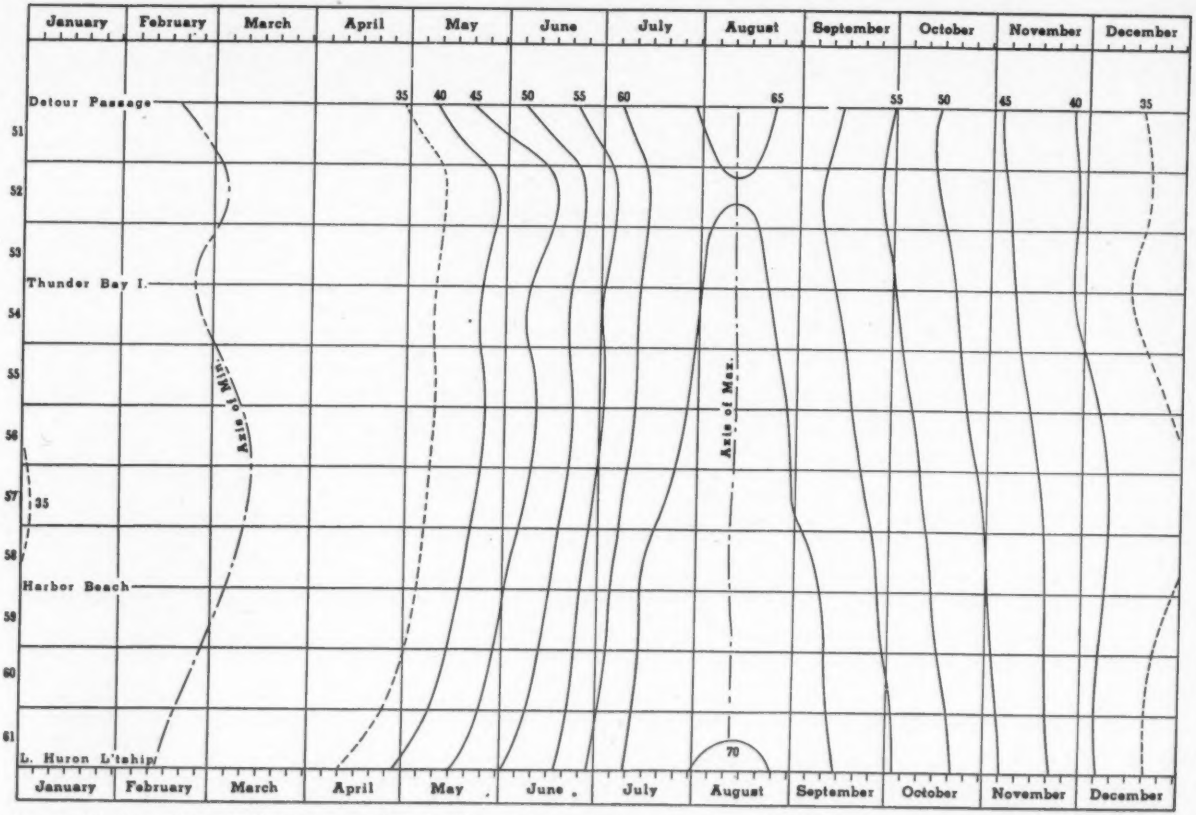


FIGURE 12. Annual march of temperature in Lake Huron between Detour Passage and Lake Huron Lightship, averaged 1936 to 1941.

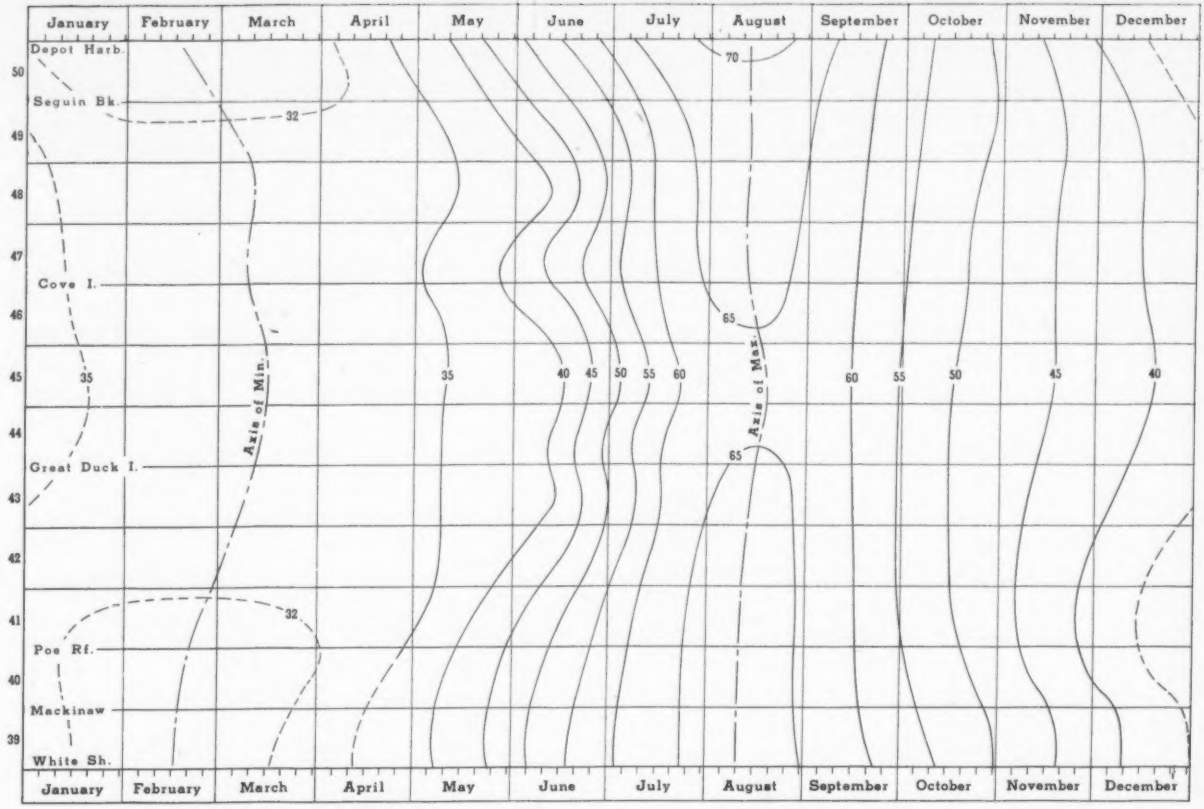


FIGURE 13. Annual march of temperature in the Strait of Mackinaw, northern Lake Huron, and Georgian Bay, from White Shoal to Depot Harbour, averaged 1935 to 1941.

normally during the warming phase. There is a strong westward current here which would confine a band of warm water against the north shore. Great Duck Island is a pinnacle on a submarine ridge which would divert the warm side of the current into the ship track for a short distance. A similar effect can often be noted on individual thermograms near Thunder Bay Island, which is situated 12 mi. (19 km.) east of Alpena.

In section 45, autumn cooling is quite slow after the middle of October. This is a very deep place suspected of being an area of upwelling.

On the east side of Georgian Bay, the spring warming is early, but autumn cooling is not likewise early. This effect seems to be the same as the westward displacement of the warmest area in Lake Ontario in late autumn: see Figure 26 for November.

The distribution of temperature over the surface of Lake Huron month by month is now to be reviewed by reference to Figures 16 to 27. For April, the supposed distribution depends on extrapolation. It is supposed that the mean temperature rises to 35° F. on southeast shores and in enclosed areas, but the temperature in midlake may be as low as 33°. Even May depends on some extrapolation. December also is extrapolated.

In the early warming phase, the isotherms tend to follow depth contours. As midsummer approaches, warm water gathers in the south end, then spreads up the east shore. In early autumn the trend of isobars southwest to northeast is present, but not so striking as in Lake Michigan. In November the movement of the warm area up the east shore is indicated by a stronger bend in the 45° isotherm than in Lake Michigan, because the large deep area between Southampton and Great Duck Island retards cooling. As in Lake Michigan a relatively cool area appears along the west shore, which is especially wide about midway between the ends of the lake, and which is attributed to upwelling.

In the months August, September and October in the inner end of the northwest arm, especially on the south side, there is a hint in the temperature distribution of some dynamic impounding of low-density water. This phenomenon has been discussed as it occurs off Port Weller in Lake Ontario, and a further example will be discussed for Lake Superior near Duluth.

Lake Superior

The temperature regime in Lake Superior differs from that in the other lakes chiefly because the lake is very much deeper. The bottom water assuredly remains at the temperature of maximum density all year, and there is no sign that bottom topography influences the surface distribution of temperature.

Then too, the winter climate in the area is colder. The January mean air temperature at land stations in the region is about 13° F. lower than in the region of the middle and lower lakes. Ice forms solidly from Isle Royal to Fort William and in other sheltered areas. Nevertheless, the main body of the lake remains free of solid ice. At the height of summer the deep water of the lake is insulated from warming by the floating epilimnion, but in winter there is little density stability

and the full depth, with its large thermal capacity, is exposed to the winter cooling. This explains why the annual mean temperature of the lake is low.

On the course from Fort William to Gros Cap, observations have been obtained for the whole season of navigation. Fort William is marked as "Welcome Islands", a landmark lying a few miles off the docks. The open lake begins farther out at Thunder Cape. Figure 14 shows the cycle of temperature through the year from Thunder Cape to Gros Cap.

The feature which first commands attention is the very localized maximum temperature in section 15 during the warming phase. This is the fourth section southeast from Passage Island. Superficially this resembles the thermal evidence of a current which has been noted in Lake Michigan off Point Betsie and the Sleeping Bear, but it has a different cause.

Harrington did not find a single drift course crossing this section. However, one drift of wreckage was supposed to have passed eastward through section 17, but could have passed through section 15. At any rate there is not much current through section 15, or some of the many drifts that rounded Keweenaw Point would have been drawn into it. The actual current system consists of two cyclonic whirls, one centred about 50 miles (80 km.) east-southeast of Passage Island, the other centred a little west of Caribou Island. In Figure 5 illustrating the currents, the shear zone between the whirls, and the separate identities of the whirls, have been emphasized more than in Harrington's original diagrams.

The cyclonic whirls necessarily possess a saucerlike topography of the surface in each whirl. A ridge of high exists between the whirls, and this ridge passes through section 15. An area of relatively high surface must contain water of high specific volume. As in the density current equation, a shallow epilimnion and prevailing temperatures not much above 39° F. favour a large anomaly in the surface temperature. As soon as the autumn thermal overturn begins the anomaly of temperature disappears, as with a density current. It is not necessary to postulate a strong current to explain this local maximum.

The maximum is repeatedly present in the same place in successive tracings. The sample thermogram, Figure 3, displays it.

Another thing to be noted in Figure 14 is the extremely slow rate of cooling in autumn, due to the great depth of the lake.

Attention is now turned to Figure 15, showing the change of temperature with time on the course from Duluth to Fort William. July and August were the only months of actual observations, but the figure has been extrapolated for the year by supposing that the 35° isotherm would occur near shore at about the same time as near shore on the other course, and at about the same time near Grand Marais, Minnesota, as in the open lake on the other course.

It is evident that a strong current is present in section 4, which is 20 to 30 miles (30 to 50 km.) north of Devil's Isle. From the chart of currents this is identified as the current which passes westward all along the north shore and here turns southward, then to follow the south shore to Duluth. The original bottle drifts recorded by Harrington are instructive, seeing that all bottles dropped west of Devil's Isle reached shore near Duluth. The arm west of Devil's Isle is an area of

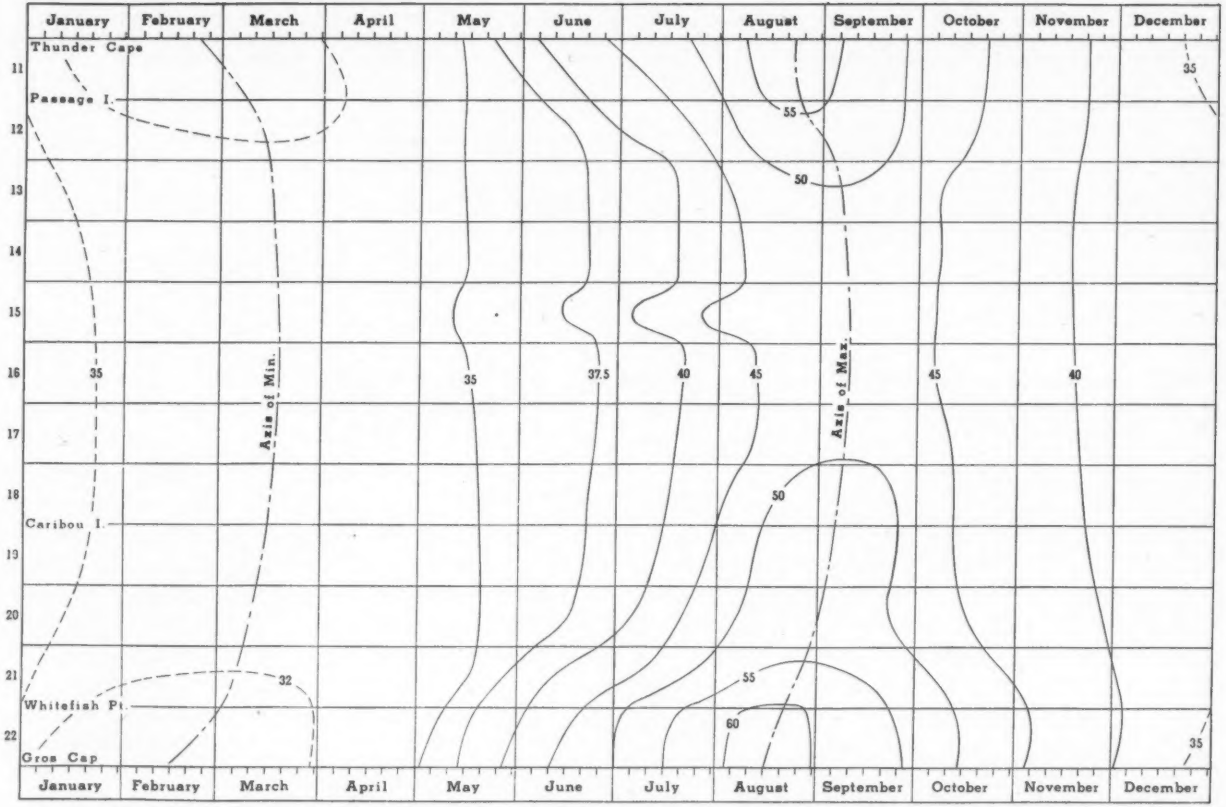


FIGURE 14. Annual march of temperature in Lake Superior between Thunder Cape and Gros Cap, averaged 1935 to 1939.

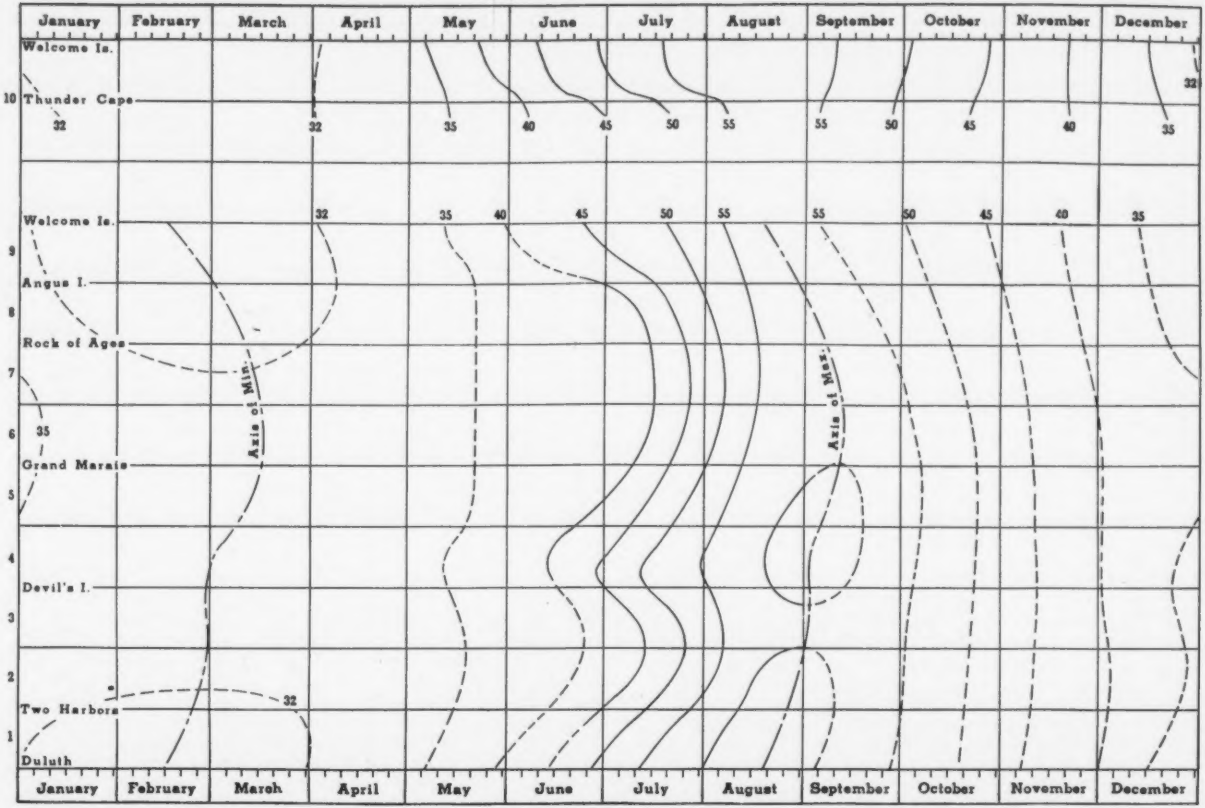
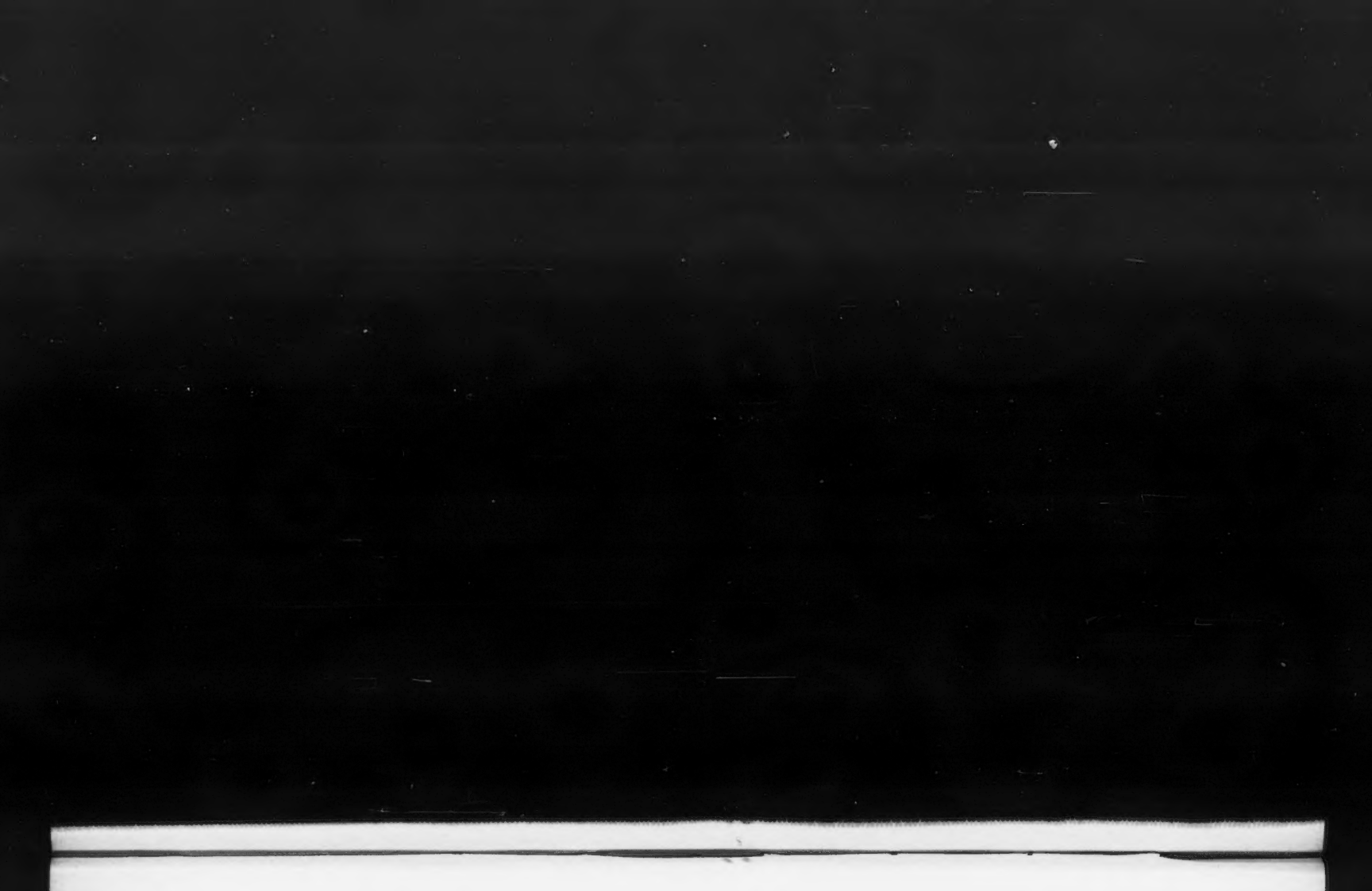


FIGURE 15. Annual march of temperature in Lake Superior between Duluth and the Welcome Islands near Fort William averaged 1937 to 1939; also between the Welcomes and Thunder Cape 1935 to 1939.



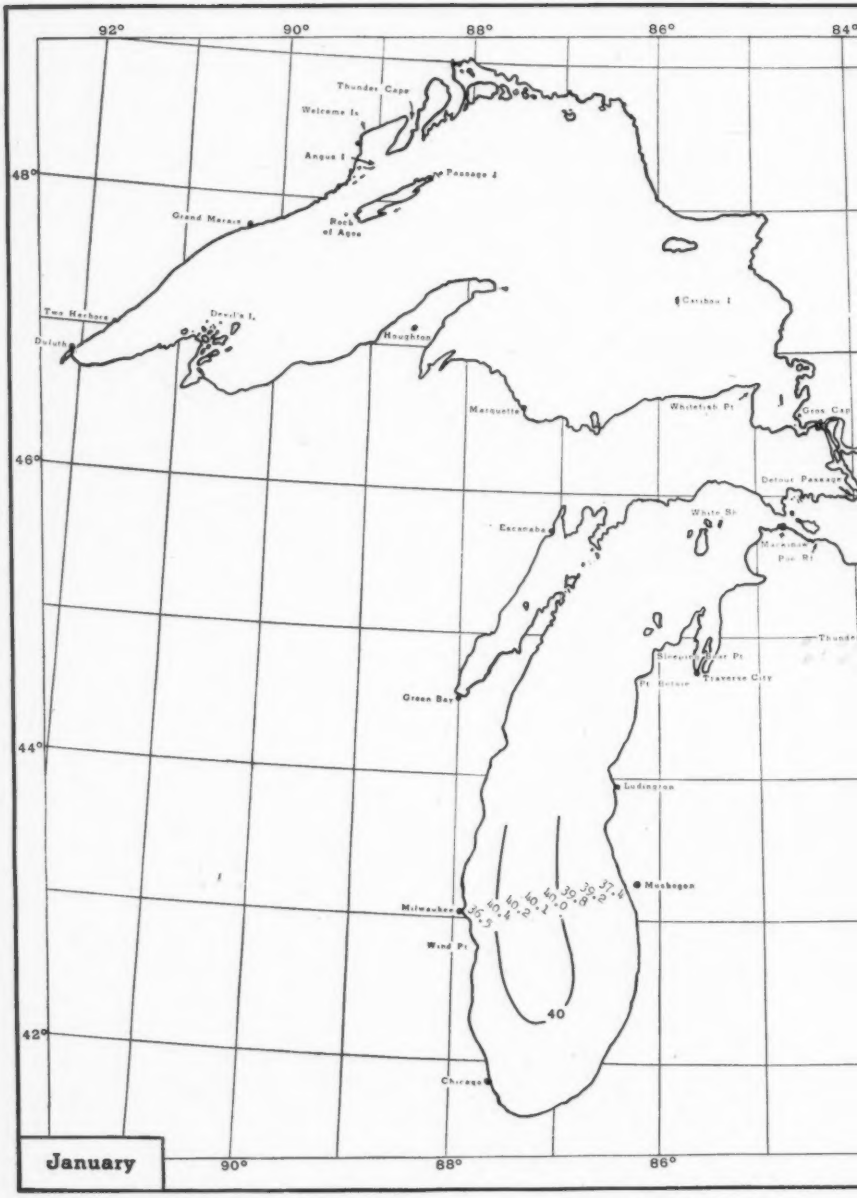
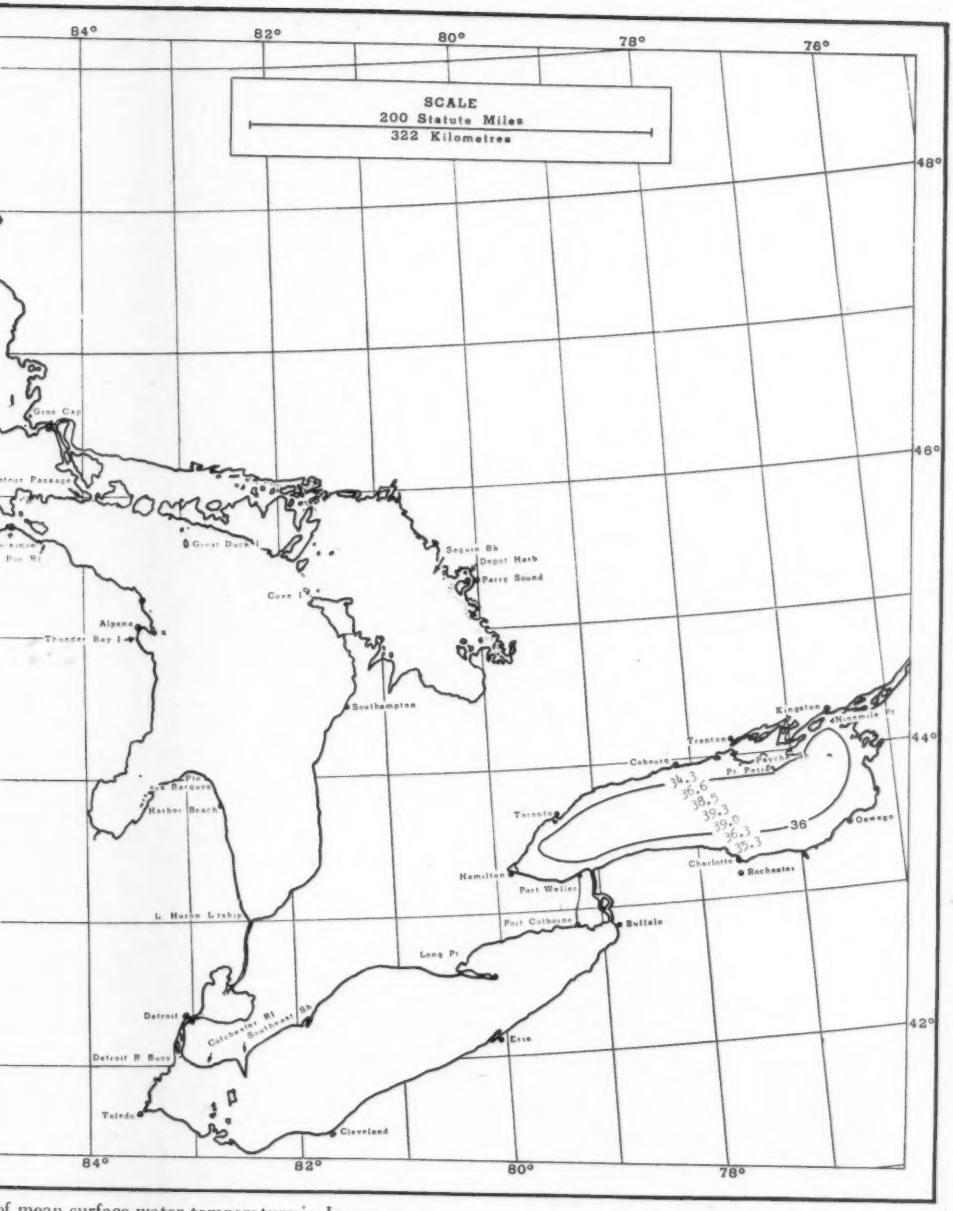


FIGURE 16. Distribution of mean



of mean surface water temperature in January.

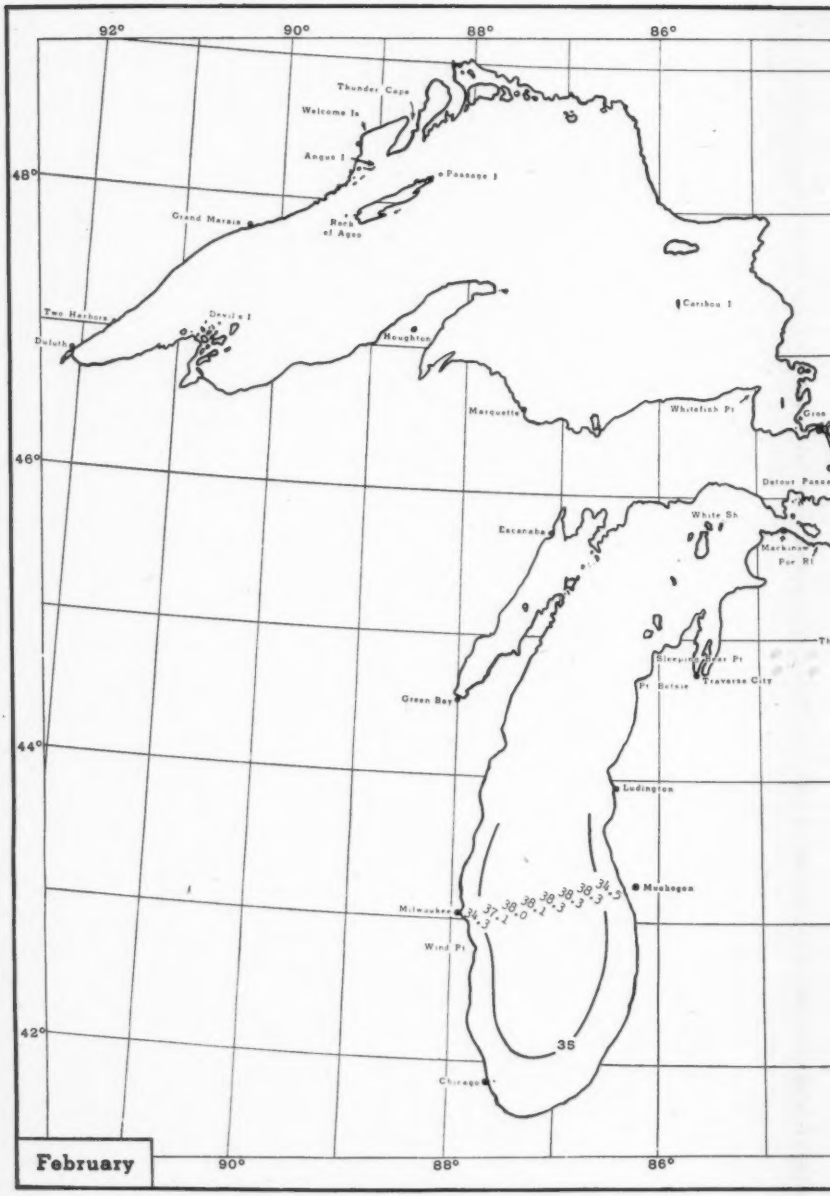
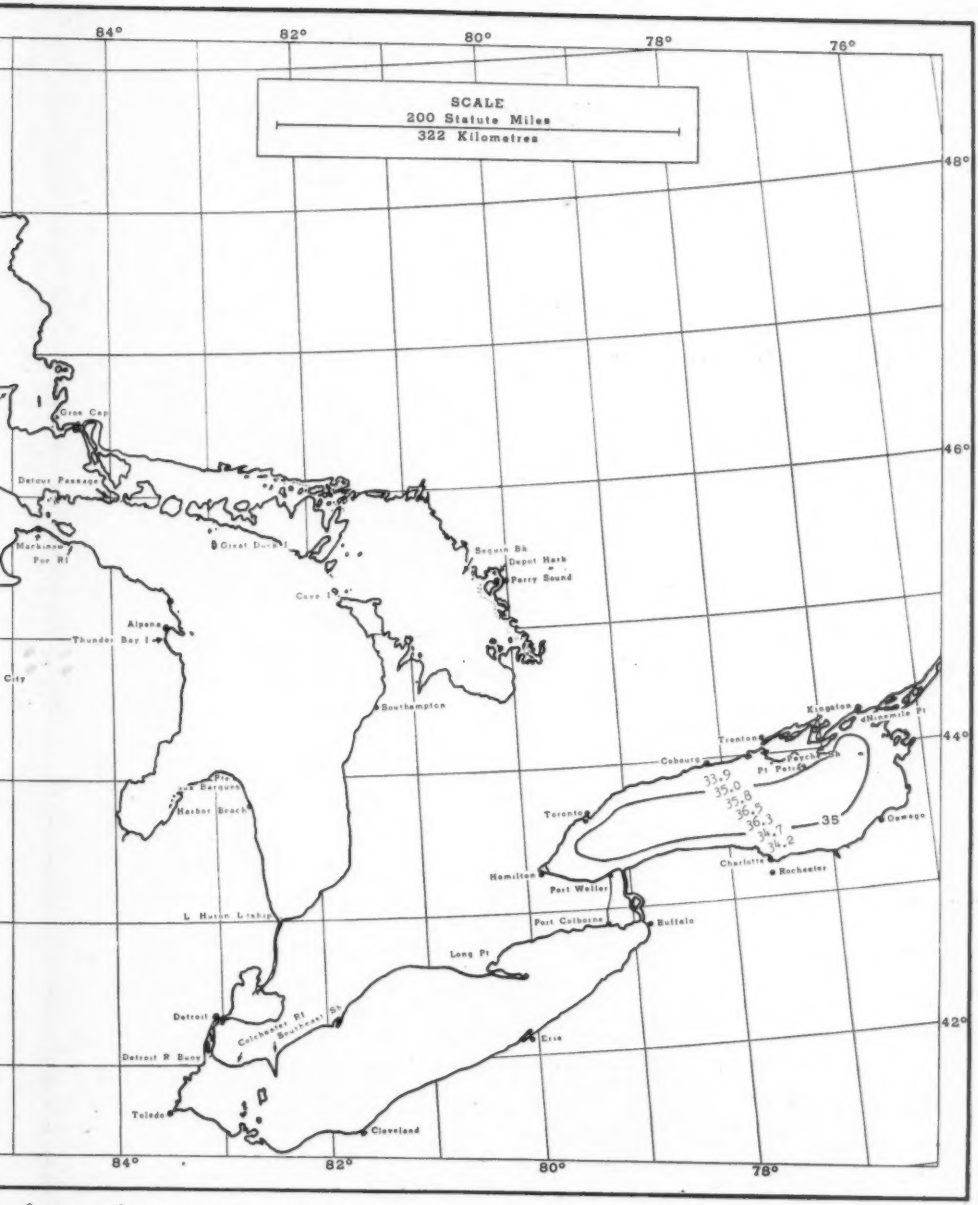


FIGURE 17. Distribution of mean



n of mean surface water temperature in February.

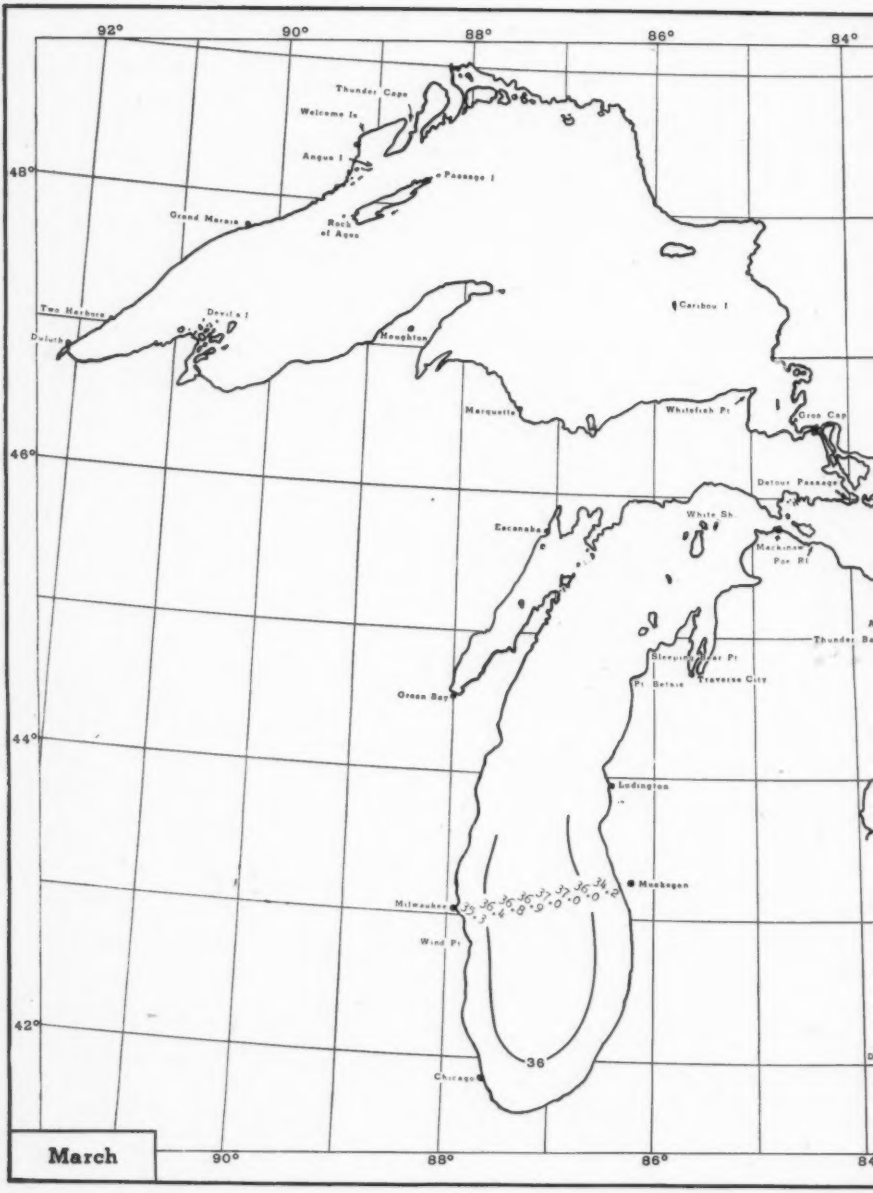
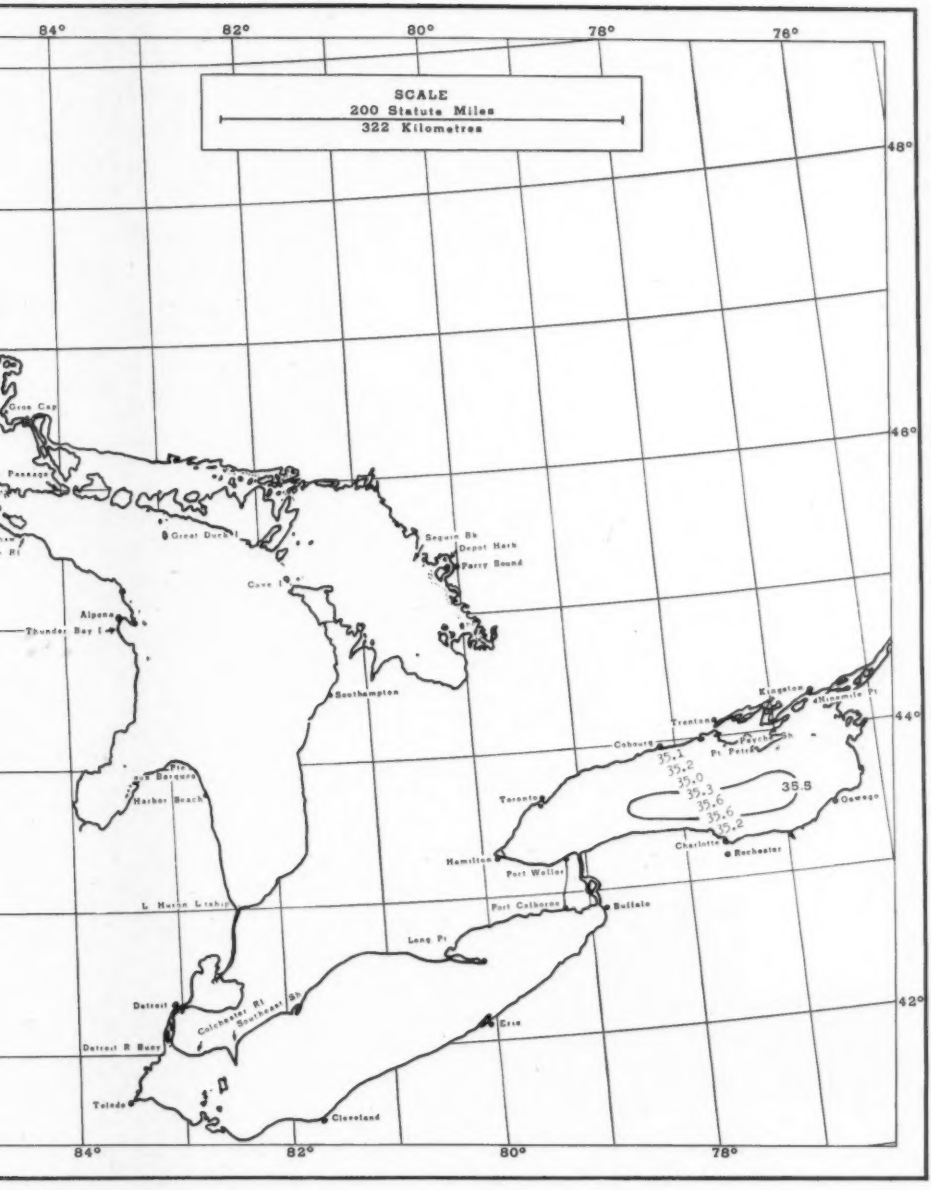


FIGURE 18. Distribution of mean sur



of mean surface water temperature in March.

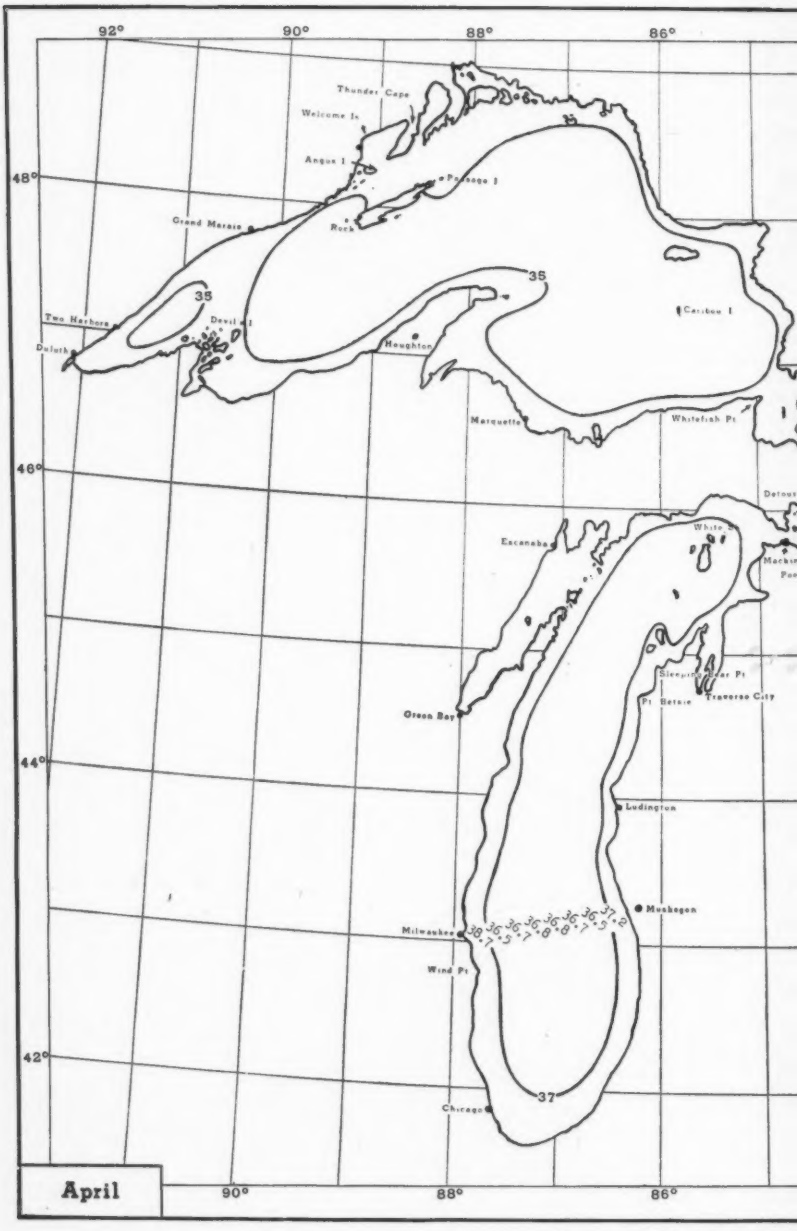
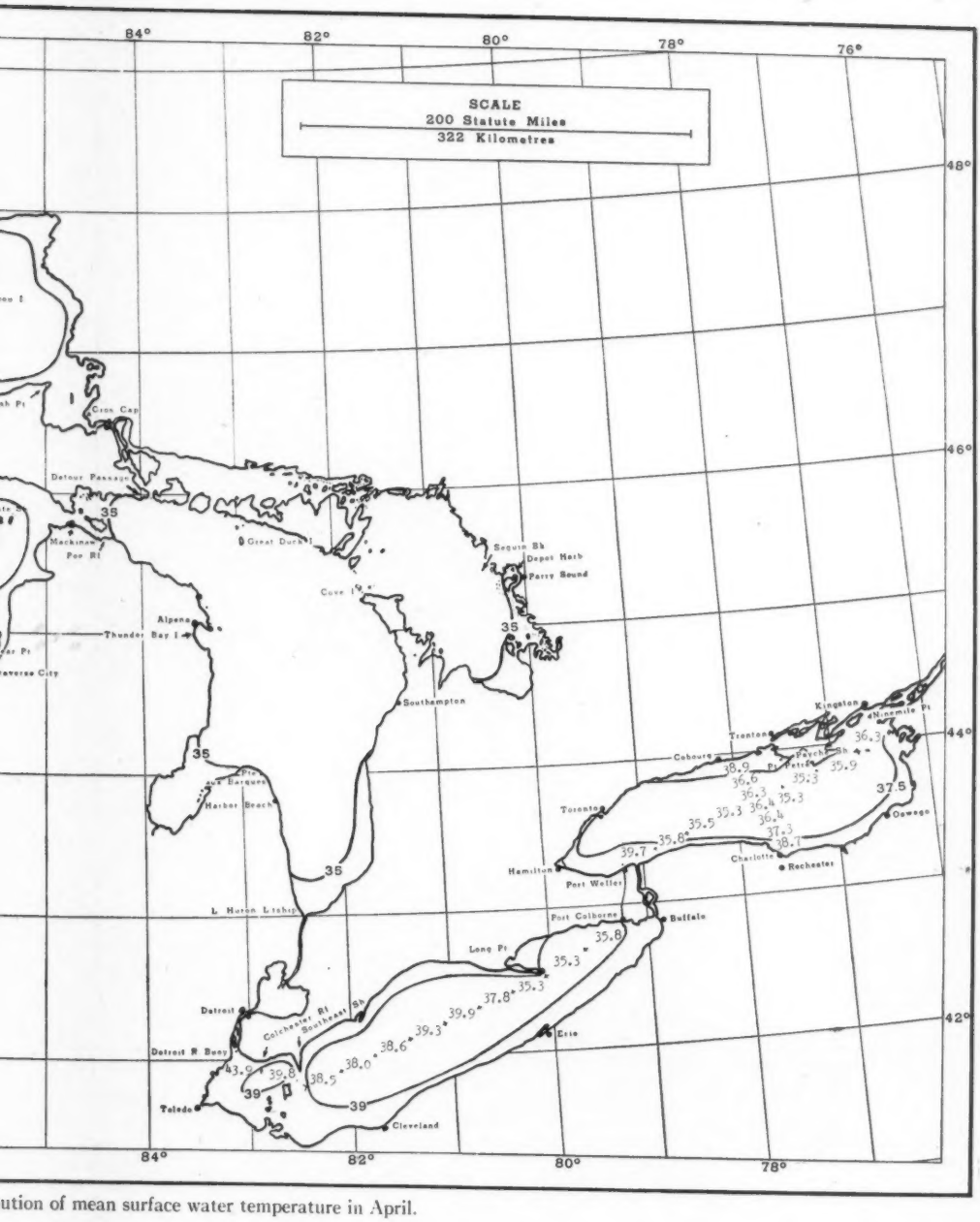


FIGURE 19. Distribution of



ution of mean surface water temperature in April.

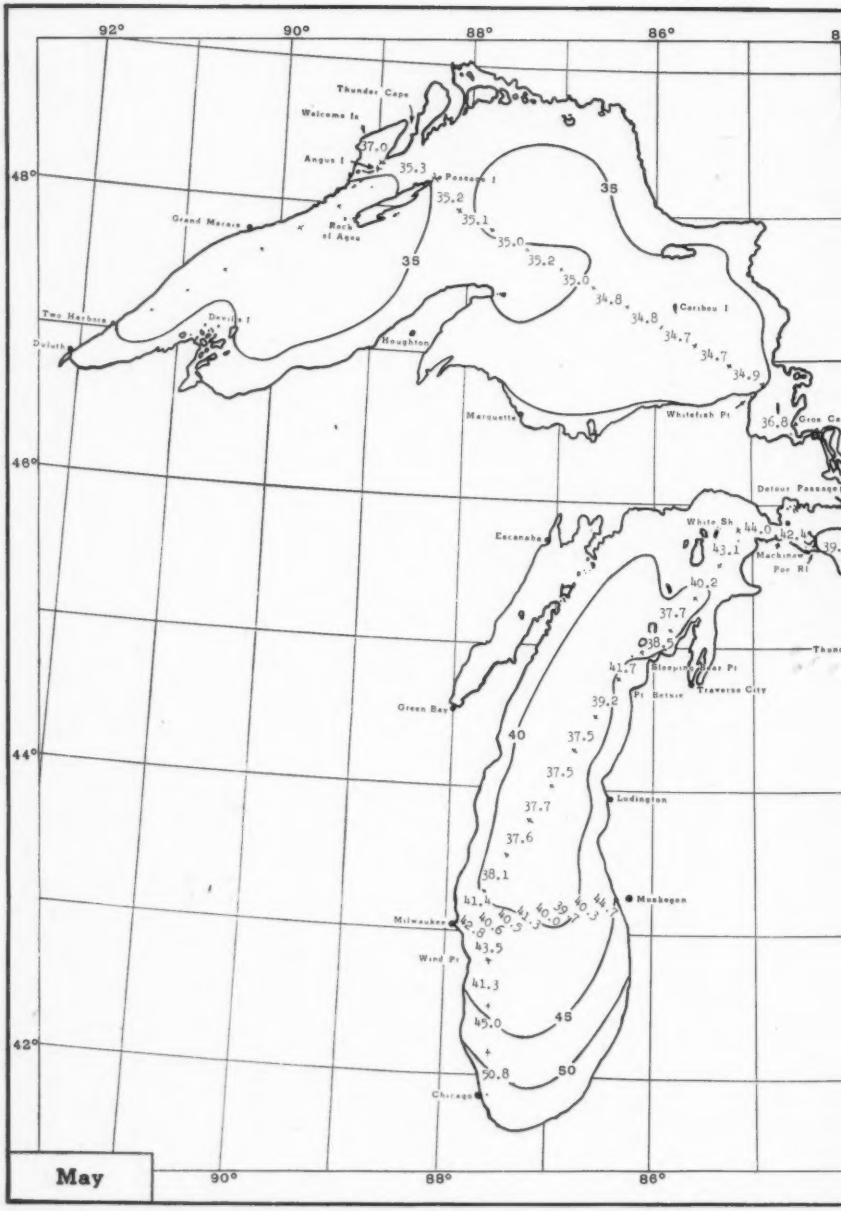
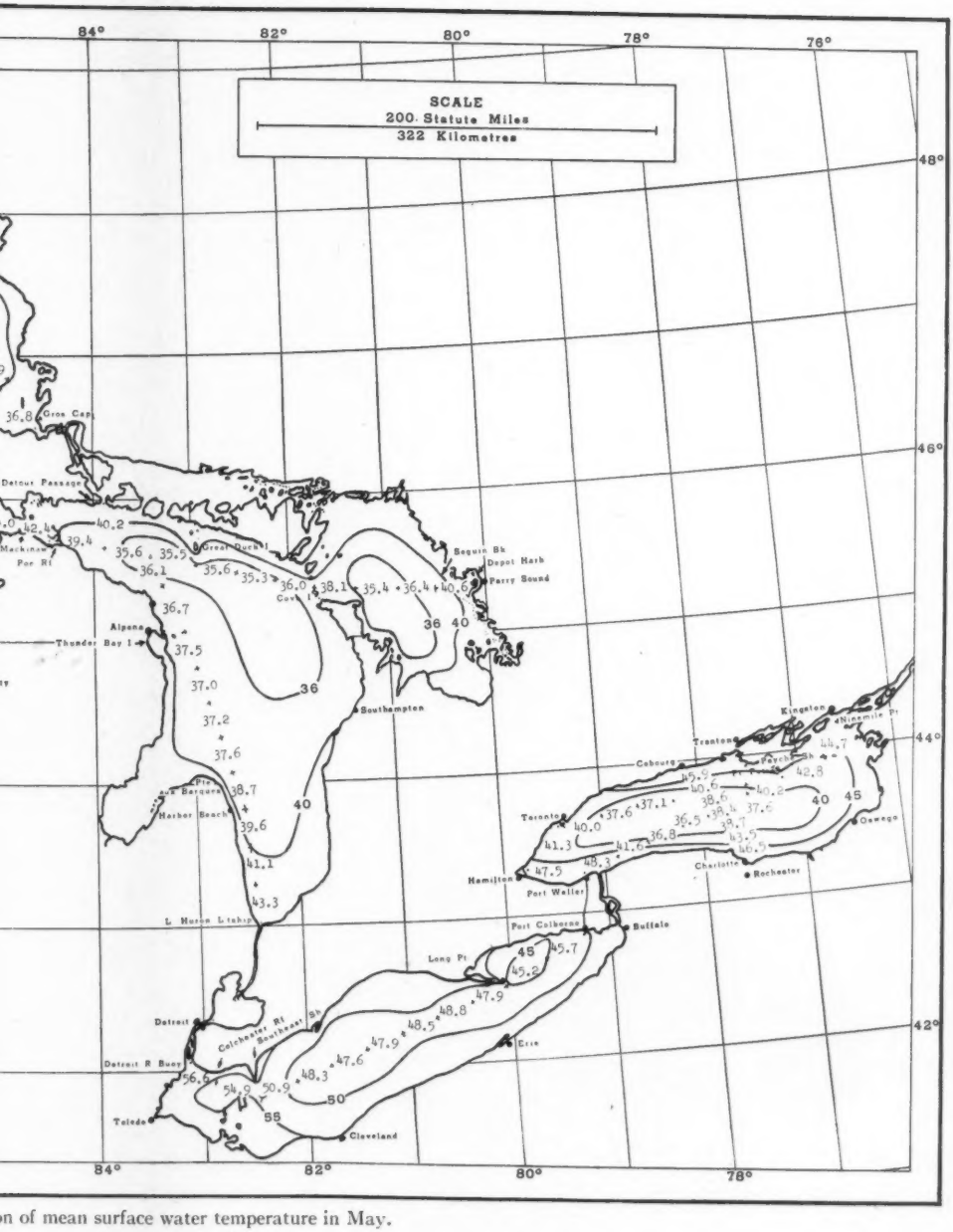


FIGURE 20. Distribution of mea



on of mean surface water temperature in May.

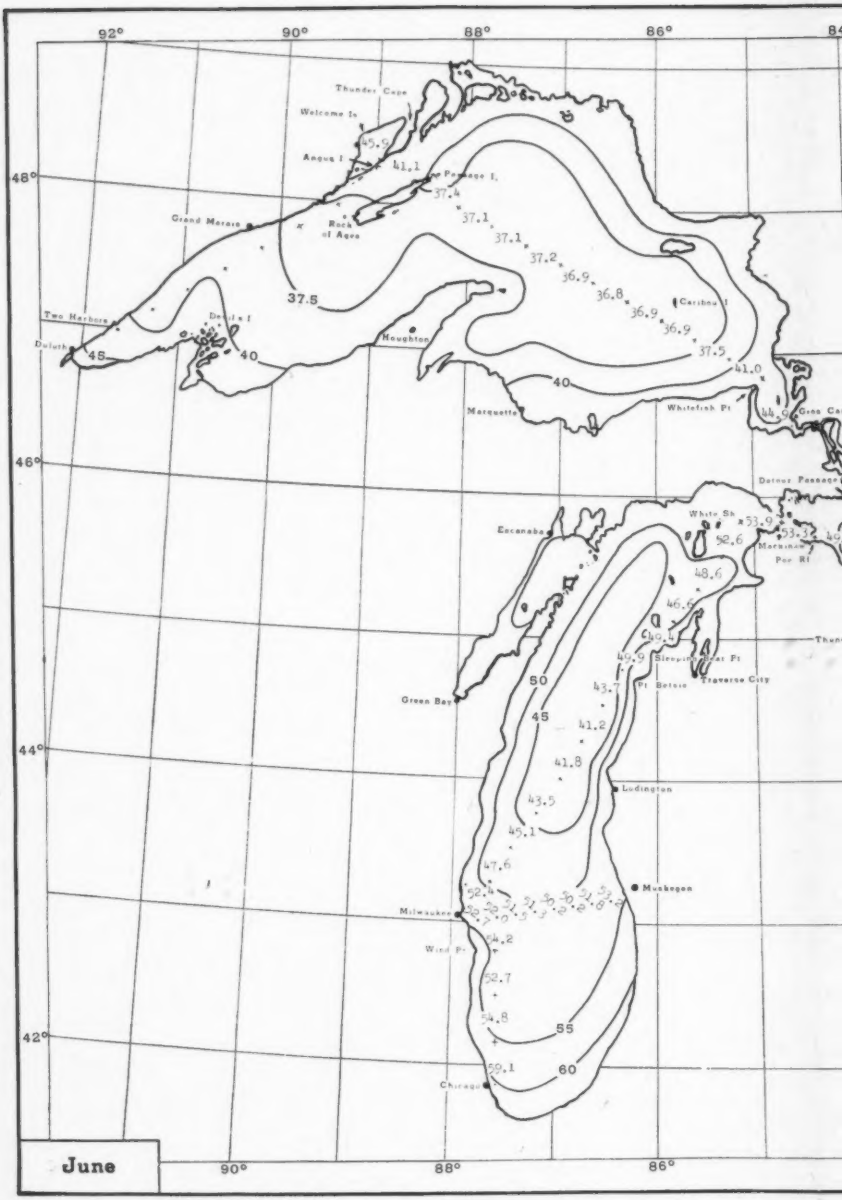
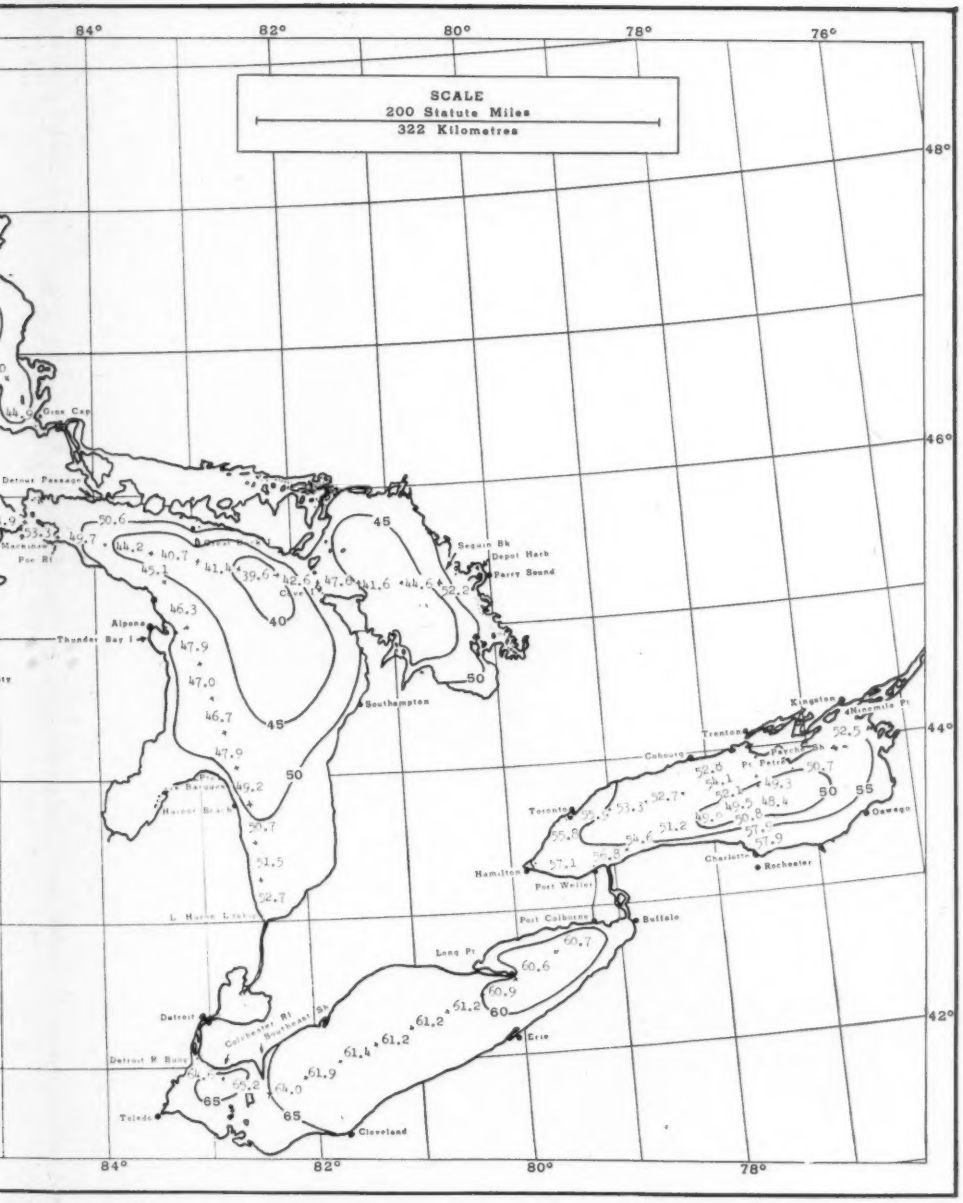


FIGURE 21. Distribution of me



ion of mean surface water temperature in June.

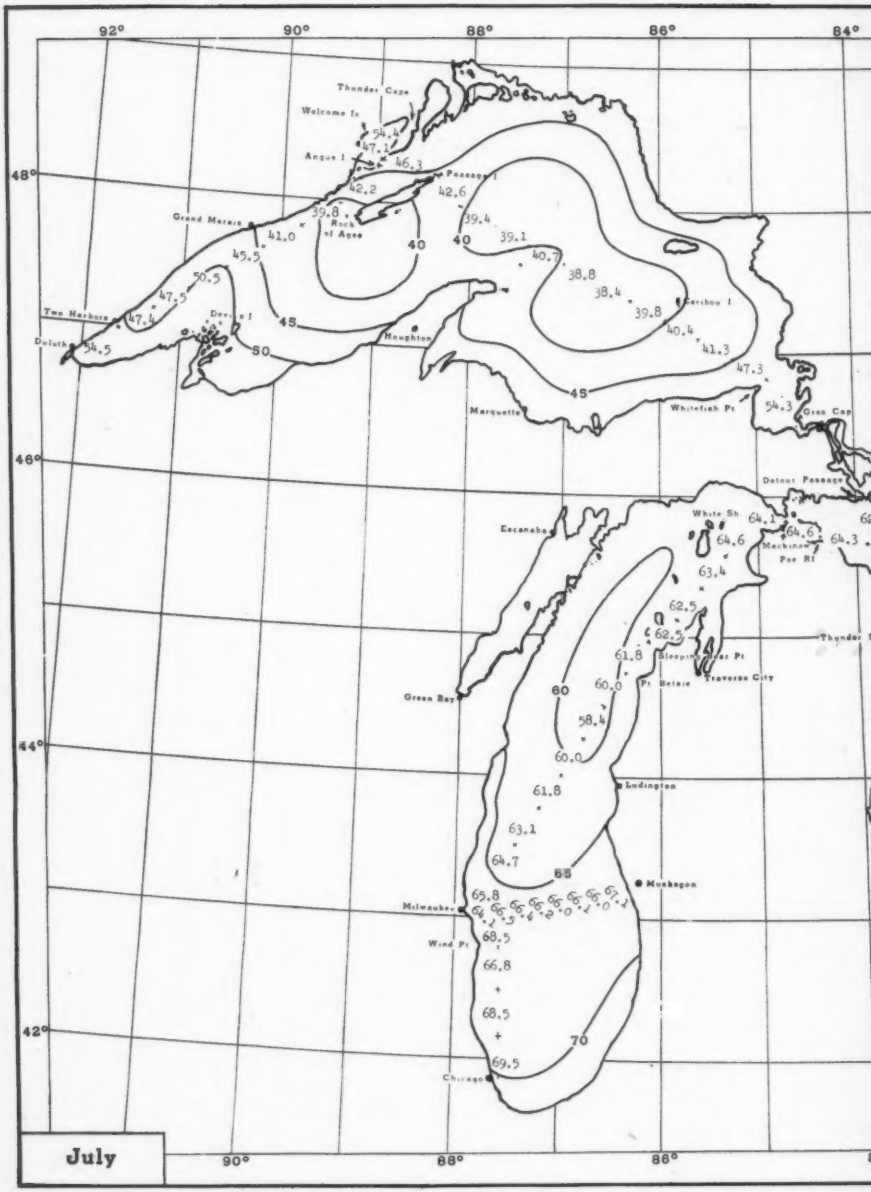
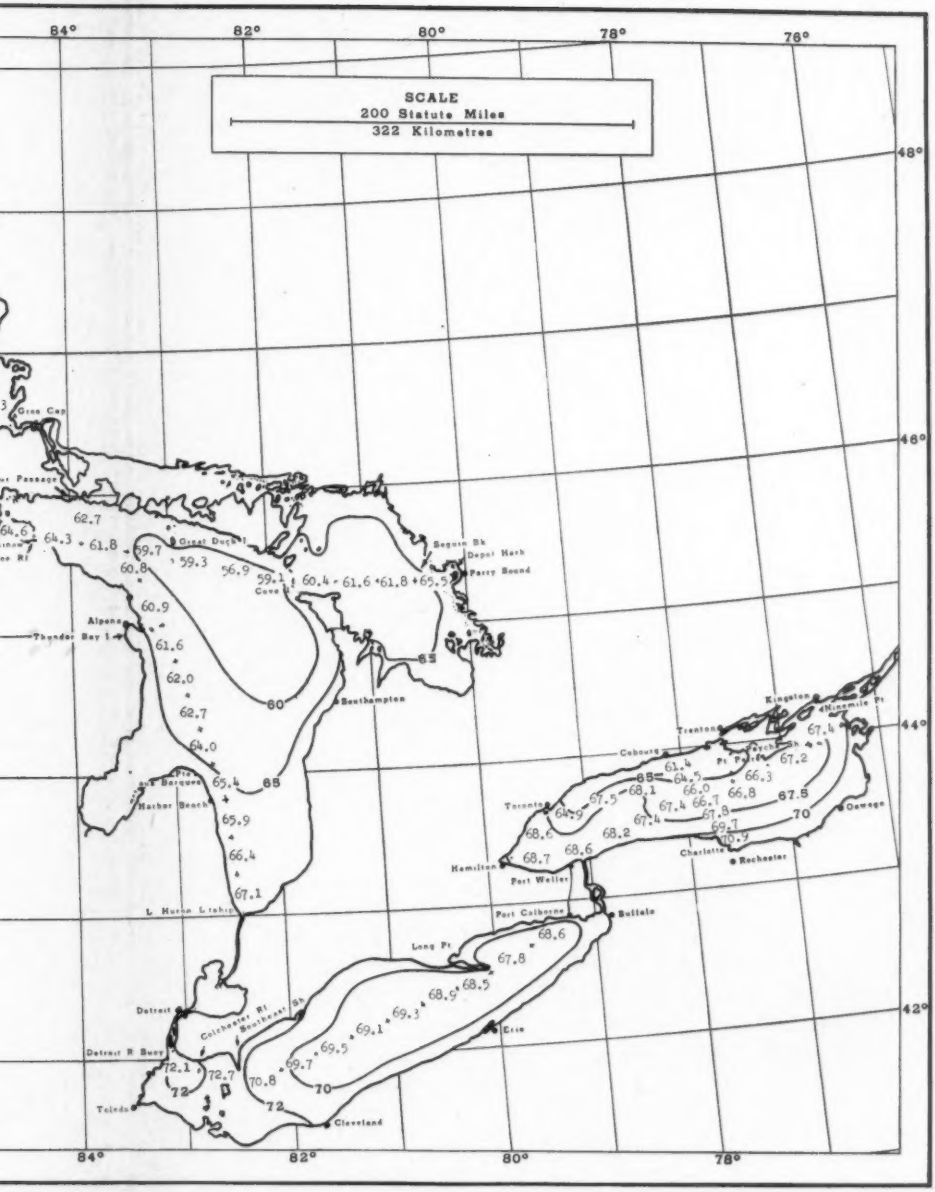
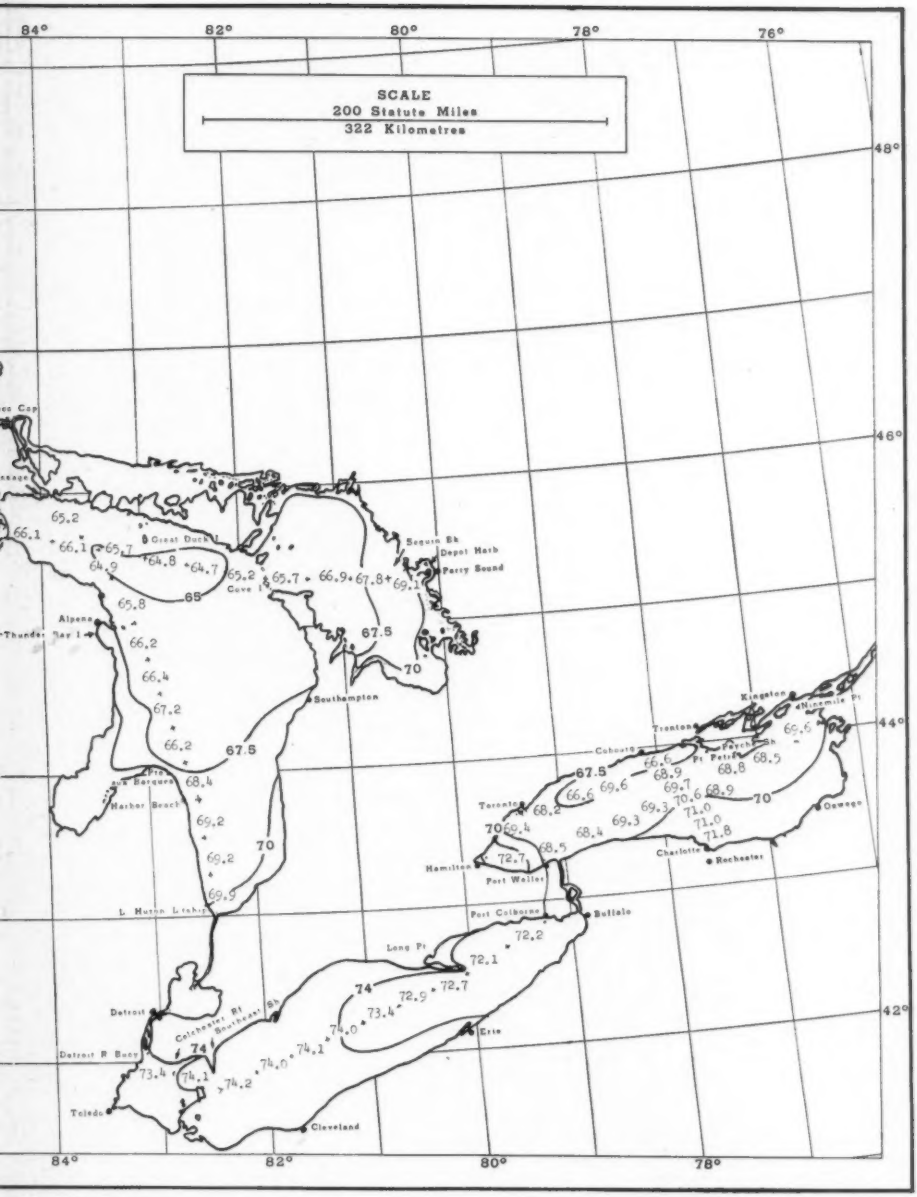


FIGURE 22. Distribution of mean s



of mean surface water temperature in July.

FIGURE 23. Distribution of mean surf



mean surface water temperature in August.

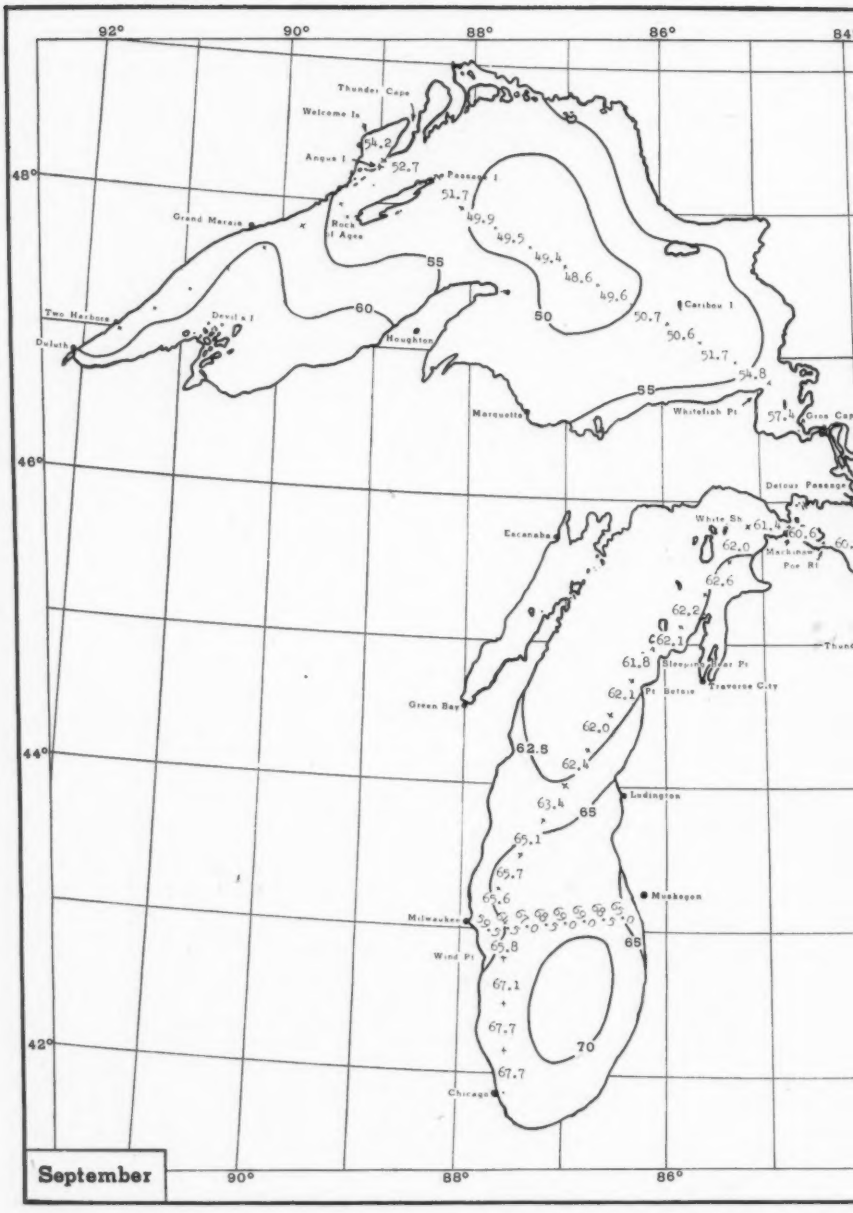


FIGURE 24. Distribution of mean s

of mean surface water temperature in September.

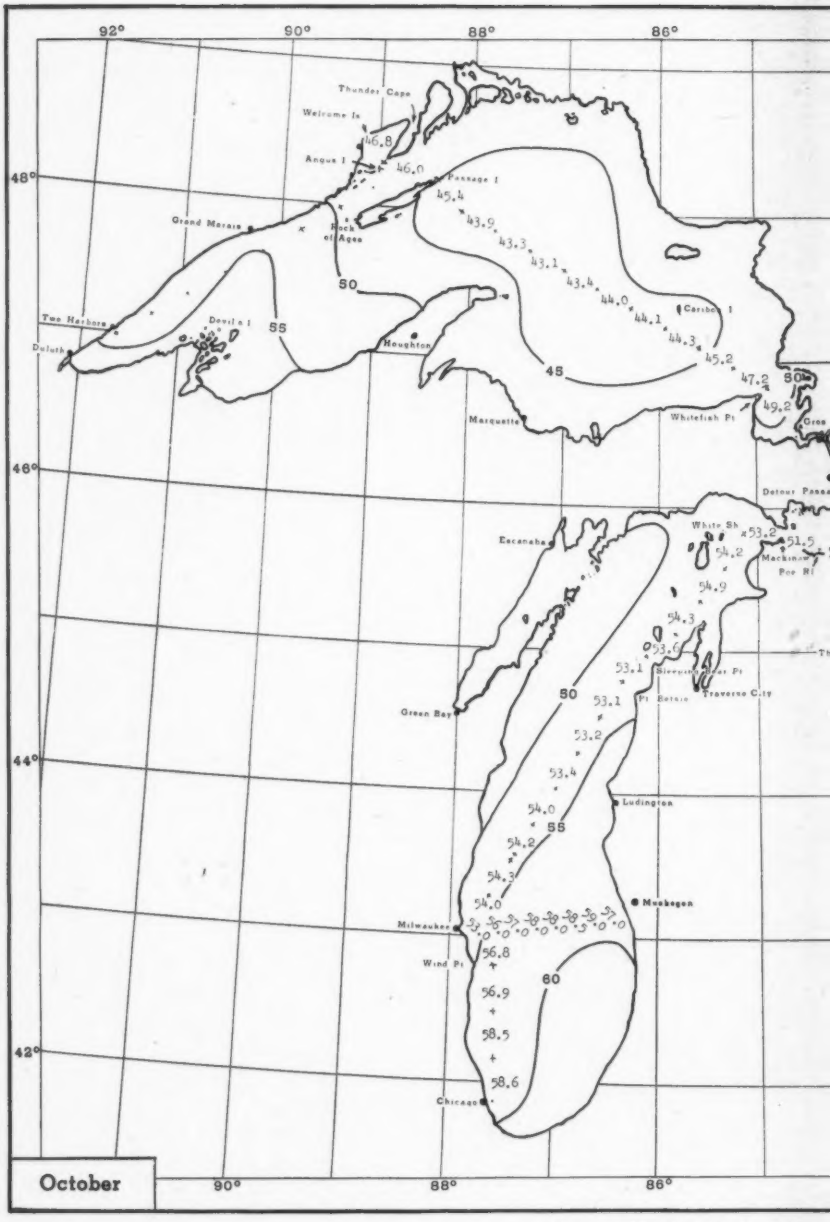
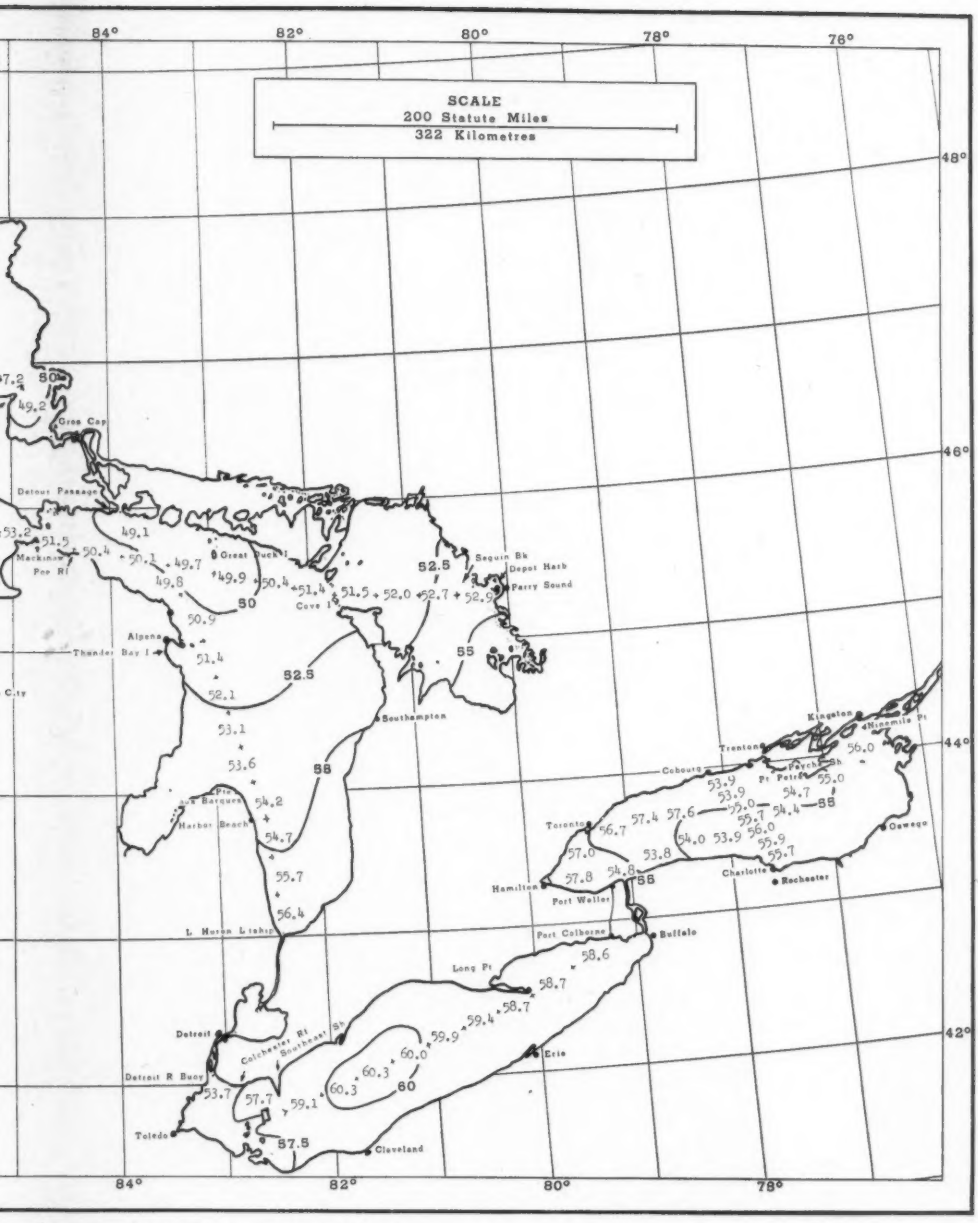


FIGURE 25. Distribution of mea



on of mean surface water temperature in October.

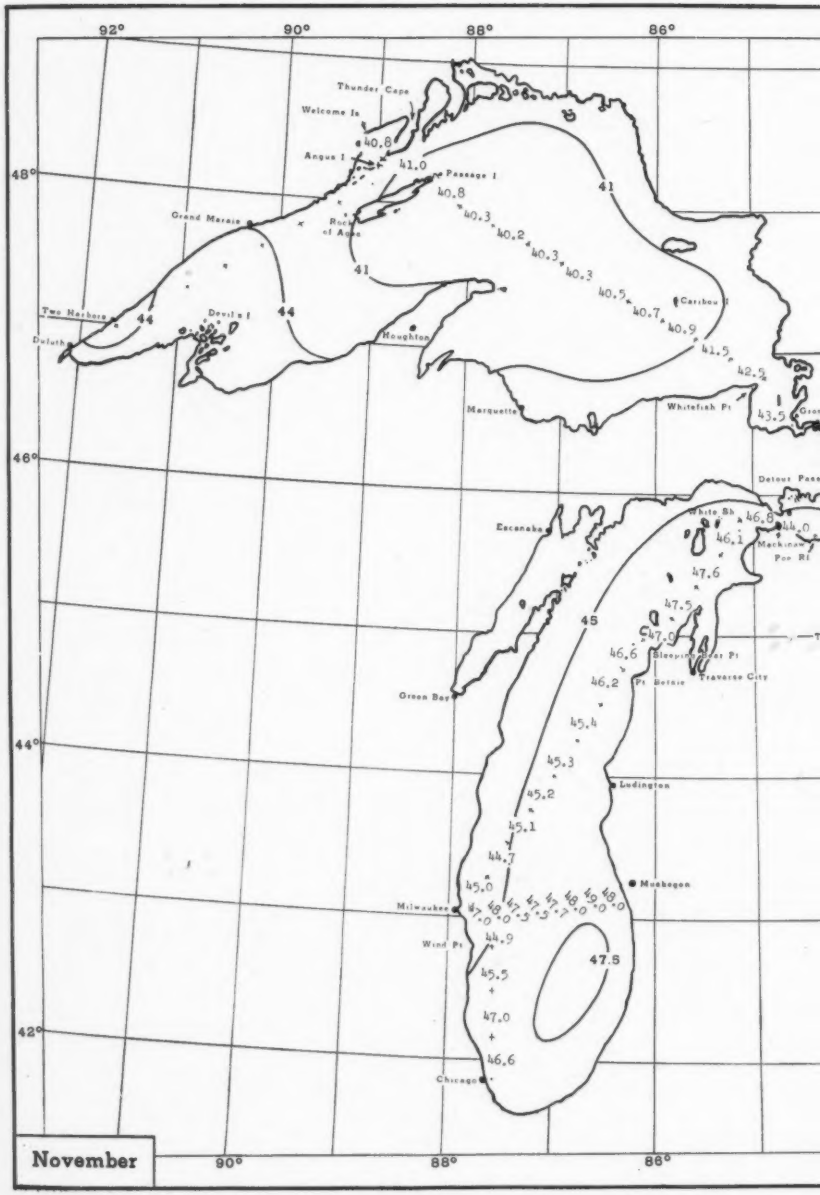
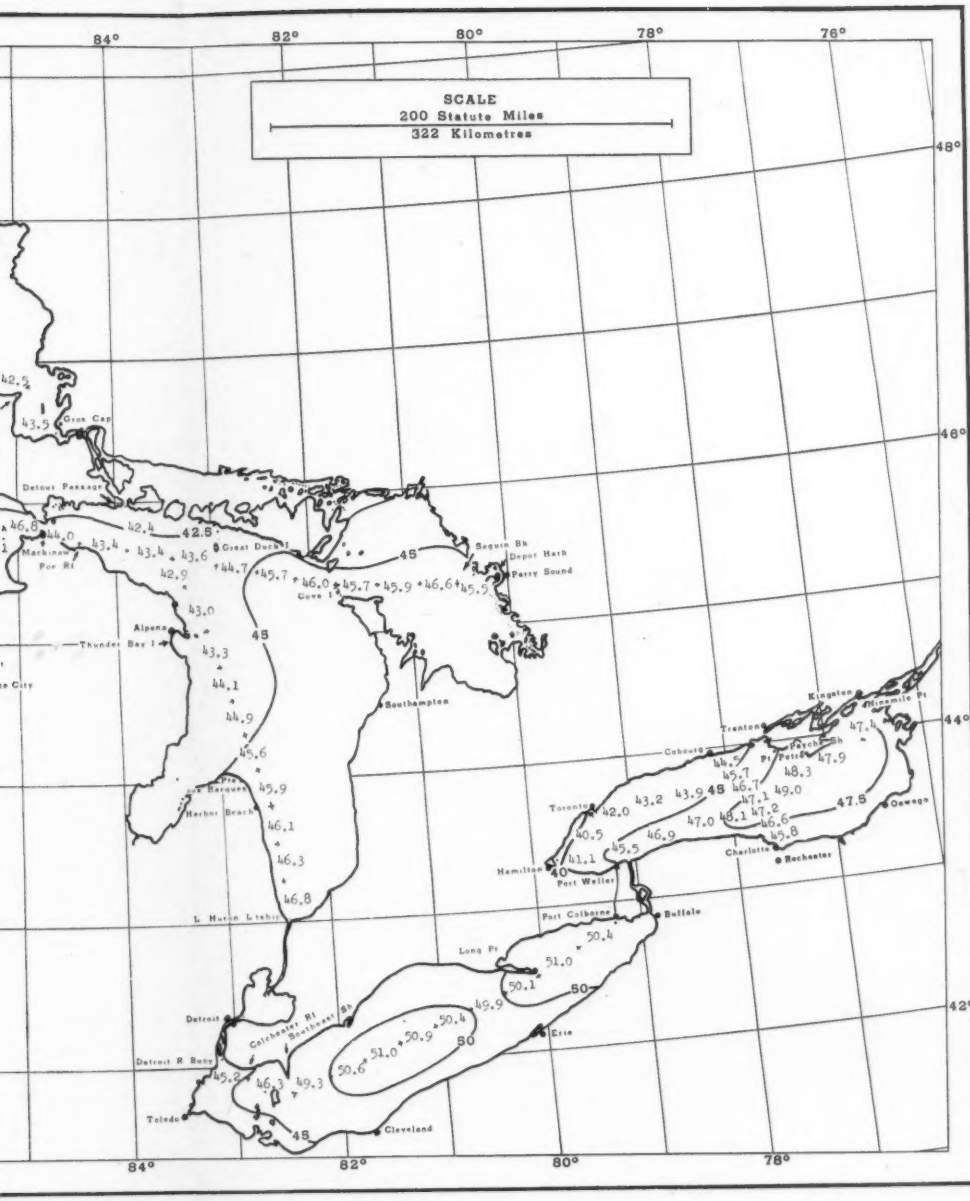


FIGURE 26. Distribution of mea



ion of mean surface water temperature in November.

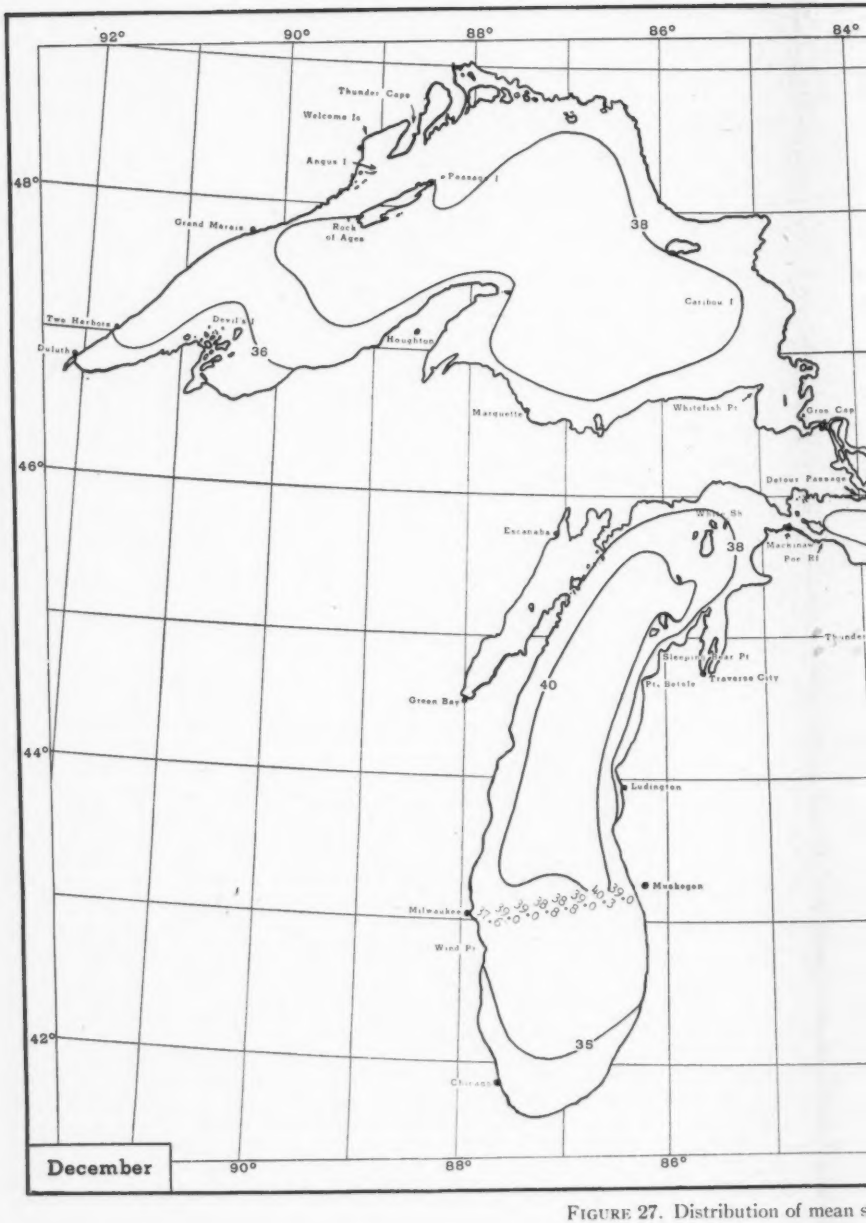
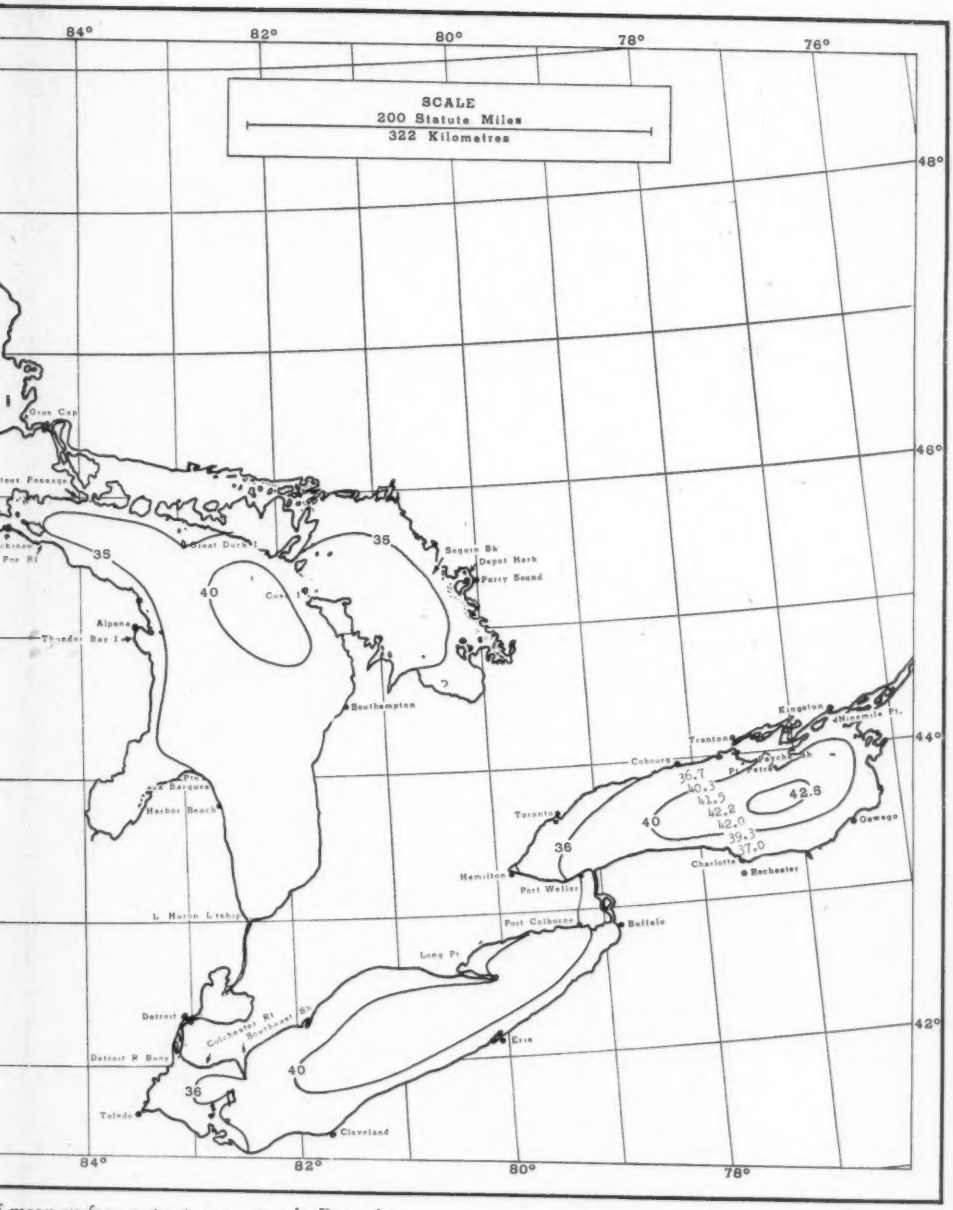


FIGURE 27. Distribution of mean s



f mean surface water temperature in December.

strong convergence; streamlines do not exit from the area. Warm surface water is impounded there and is subject to downsinking. This is supported by the temperature observations, for a maximum temperature above 60° is attained in the main current and in the impounded area near Duluth. An equally high maximum is attained nowhere else on the lake save inside Whitefish Point. The water in the western arm is deep, so there is no question of warming in shallows. The warm water collected in the area originates along the north shore.

Sections 9 and 10, next to Fort William, are both shown at the top of Figure 15. Although the courses lie close together it has not been possible to draw the isopleths exactly alike. The difference could be largely due to errors in chart reading, for with the strong temperature gradients in Thunder Bay, a small error in timing the landmarks would effect the tabulated temperature.

The distribution of temperature over the lake, month by month, is shown in Figures 16 to 27. It is not possible to make any firm deductions as early as April, only it seems by extrapolation that the temperature may be as low as 33° or 34°. In May and June the places where isotherms cross the one available course are determined, but elsewhere the configuration of the isotherms is conjectural. By analogy with the other lakes, they are supposed to parallel the shore wherever possible.

The two cyclonic whirls in the east end of the lake, especially the more southerly one, are areas of convergence, and the arm near Duluth is an area of strong convergence. The compensating upwelling is distributed broadly south of a bent line from Devil's Isle to Passage Island, thence to Marquette, Michigan. No bottle drifts entered this area, and all originating in it left the area except a few that terminated ashore.

The first section southwest of Passage Island, number 12, is warmer every month than the next two sections southeast. The warm water from the north shore does not all pass north of Isle Royal, but some swings south near Passage Island, on the west side of the cyclonic whirl in the north central area. In the absence of any temperature observations south of Isle Royal, a ridge of slightly higher temperature has been inferred, extending south from Passage Island. Until the end of August, this ridge is limited on the west by upwelling south and southwest of Isle Royal. In later months the warm area of the western arm is considered to have spread eastward, just as the warm areas of convergence spread in the other lakes.

All through the high temperature season, even as late as November, isotherms in Lake Superior tend to run parallel to the shore. Midlake never warms up much. It is only in December that it becomes colder near shore than in midlake.

MEAN MONTHLY TEMPERATURES OF THE LAKES AS A WHOLE

The maps of the monthly isotherms for surface waters of the Lakes show that the average temperature of a lake as a whole has limited significance. There is so much change from one part to another of one lake that the average of the whole surface gives little idea of the temperature at a selected locality.

However, the averages may have some uses, and are accordingly set forth in Table II. To construct the table, areas between isotherms were measured with a planimeter, and an average temperature for each area judged by inspection. The weighted monthly averages for each lake, and for the Lakes as a whole, were then computed. Because of the doubt in the placing of isotherms, these averages are only accurate to the nearest degree, more or less.

TABLE II. Average surface water temperature of lakes as a whole, in degrees Fahrenheit.

	Superior	Michigan	Huron-Geo. B.	Erie	Ontario	All
Jan.	—	—	—	—	37	—
Feb.	—	—	—	—	35	—
Mar.	—	—	—	—	35	—
April	—	—	—	—	37	—
May	35	41	39	50	42	40
June	39	51	48	63	54	45
July	44	61	64	70	67	57
Aug.	55	69	68	73	69	64
Sept.	54	65	61	67	65	61
Oct.	48	54	54	59	55	52
Nov.	42	46	45	49	45	44
Dec.	—	—	—	—	39	—

DEVIATIONS OF LAKE SURFACE TEMPERATURE FROM THE NORMAL

In this section standard deviations of lake surface temperatures are found, also the correlation between the deviations in observations a few days apart. These data lead to estimates of the probable error of monthly normals. By one formula, the autocorrelation affects the estimate of the probable error. This correlation also makes possible a forecast of the temperature of a lake when observations are available of the temperature a few days before the time of the forecast.

Quite a few of the numbered sections of the Lakes were selected as samples, and the temperature observations were plotted on the date in the year as base (diagrams not reproduced). A normal annual curve was sketched through the array of points. The scatter about the curves varied through the year, but was much the same on all sections. On this account only two sets of data were selected for further study: (*a*) the space average between Cobourg and Charlotte, because of the long period of observation; (*b*) the space average between Fort William and Gros Cap in Lake Superior, because of the exceptional annual cycle.

The "space average" referred to here is the average of all sections between the landmarks on a single voyage.

Notation: x = anomaly of temperature, difference between an observed temperature and the normal for the day

x_o, x_p: two values of x observed p days apart

m = number of observations in an individual month

n = number of years of observation

$\sigma_o = \left(\frac{1}{mn} \Sigma x_o^2\right)^{\frac{1}{2}}$, standard deviation of x-values

$r_p = \frac{1}{mn\sigma^2} \Sigma x_o x_p$, coefficient of correlation between x_o and x_p

$r_p^{1/p}$ = "the persistence"

s = standard deviation of the arithmetic mean

σ_p = standard deviation of x_p from value predicted by regression equation

Standard Deviations and Serial Correlations

Values of the anomaly of temperature for the day, x, have been treated as homogeneous for each month, since this particular variable is subject to seasonal effects of a low order only. Monthly values of the standard deviation and serial correlations of x have been found. On Lake Ontario so many observations were available that only about 100 were used for each diagram or computation, but those used were selected by a rule distributing them impartially through the body of data. On Lake Superior, on account of the fewness of observations, the only serial correlation found was for observations 3 or 4 days apart, the period being taken as 3.5 days nominally. The results are presented in Table III.

Table III. Standard deviations and serial correlation coefficients.

Section	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
L. Ontario 89-100													
σ° F.	.23	.22	.29	.26	.25	5.76	4.85	3.13	3.71	2.10	1.86	1.04	—
r_1	.72	.82	.85	.56	.94	.90	.86	.77	.95	.83	.89	.83	.83
$r_4^{1/4}$	.94	.94	.95	.81	.98	.94	.84	.85	.92	.91	.93	.97	.92
$r_8^{1/8}$	.93	.94	.95	.85	.96	.96	.74	.75	.83	.90	.96	.99	.90
L. Superior 10-22													
σ° F.	—	—	—	—	.7	1.0	1.4	3.2	1.5	1.6	1.2	1.0	—
$r_{3.5}^{1/3.5}$	—	—	—	—	.75	.80	.61	.52	.50	.50	.74	.82	.79

For Lake Ontario the first trial investigation was made on a five-year period (1937 to 1941), supplemented with additional material from the next two years for months that had few observations. Trends were noticeable in the values, and to verify them the same processes were independently repeated on data from 1944 to 1946. The same trends were noted. The results were therefore combined with weights 5 and 3. In the correlation coefficients, the average difference between like members of the five-year and three-year sets was 0.022, and this figure was the same for r_1, r_4 and r_8 respectively. This is taken to mean that the correlation coefficients are uniformly significant to the second place after the decimal point. At a guess, the correlations should have a significance of the same order for Lake Superior also.

The arrays of observations for the several coefficients of correlation were well centred on the origin ($x_o = x_p = 0$), as judged by inspection. This verified the daily

normals obtained graphically, so no adjustments have been applied to the normals, standard deviations, or correlation coefficients.

In the standard deviations for Lake Ontario, the maximum occurs in the late warming phase, which is understandable on physical grounds. The epilimnion is shallow at this time, and much warmer than the deep water. If the wind is slight, only the thermal capacity of the epilimnion is effective, which is small compared to the capacity of the full depth. If the wind is strong, the mixing penetrates the epilimnion and brings up the cold water. Under either weak or strong wind, the conditions are therefore favourable to a large variability in temperature.

Following the maximum, a secondary minimum of the standard deviation occurs in August. This is attributed to the accumulated effect of a few weeks of the high and less variable temperatures and reduced winds of midsummer. These have permitted a thick epilimnion to be formed, so that the cold bottom water is not accessible to mixing. Yet the epilimnion is itself thick, and rather uniform in temperature, possessing a fairly large thermal capacity. These conditions favour a reduction of the variability. Following this, the onset of the stronger winds and more widely varying air temperatures of autumn bring on a secondary maximum of the dispersion. It then declines through two or three months to the winter low, as the thermal overturn gradually penetrates to the bottom and brings the total thermal capacity of the lake into effect.

In the winter and early spring, the lake is mixed to its full depth, and so is very resistant to temperature change. In fact, the standard deviation for Lake Ontario is so small as to be comparable to the errors of observation. Yet some physical dispersion does exist in the observed values since, as will be seen later, there is still some serial correlation in the anomalies.

In Lake Superior, the summer maximum of the standard deviation comes one month later than in Lake Ontario, and is not as great. This is because the stable surface layer is slower in appearing and does not develop as deeply in this lake. The ensuing secondary minimum and maximum are then slight.

The standard deviation shows the range of deviation from normal to be expected in a single observation. It is an even chance whether any actual deviation will be over or under $0.6745\ \sigma$. The range differs from month to month, but as remarked before, it is much the same in all the lakes.

If all the observations were independent, a normal obtained by averaging N observations would have a probable error of $0.6745\ \sigma\ N^{-\frac{1}{2}}$. That is, there would be an even chance that the error would be no more than this. However, the observations within an individual month are not independent, so this formula is not applicable. If the temperature departs from normal one day, there is a tendency, measured in terms of the serial correlation, for later observations to depart from normal by a lesser amount in the same sense. If the departure is maintained for some days because of the weather, there is an increased probability for the subsequent maintenance of a departure. This persistence of anomalies is due to the large thermal capacity of the lake water. Please refer to the list of notations for the definition of "the persistence".

Brooks (1948) has discussed persistence in a meteorological element, and its influence on the standard deviation of the mean. He has remarked that the persistence may vary with changes in the interval p.

In Lake Ontario, the persistence over periods of 1, 4 and 8 days respectively averaged over the year as a whole was 0.83, 0.92 and 0.90. The increase followed by a decrease was duplicated in the two sets of data. The trend was not the same month by month, but was repeated in the two groups within limits of high probability. The trends in the persistence are therefore not a statistical accident. It is significant that the months not showing this average trend are December and April, when the temperature is near 39° F. and there is no density stratification.

It has been shown that the thickness and stability of the epilimnion affect the standard deviation. When turbulence extends to a relatively great depth, the surface has a larger effective capacity. This produces a smaller dispersion and should produce a greater persistence. In August the epilimnion is deep and stable, resistent to turbulence, so a minimum of the one-day persistence is found. In one day the turbulent diffusion does not bring the capacity of the whole epilimnion into effect, but apparently in four days it does. In eight days the turbulence may break through into the deep water thus breaking the continuity. These speculations explain the maximum of persistence on the four-day period.

The one-day persistence has minima in January and April which require a different explanation than has been offered for the August one. At these times the temperature of the lake is generally near 39° F., which is favourable for the manifestation of temperature gradients according to the density current equation. These are seasons of strong temperature gradients near shores.The low one-day persistence is therefore explained as due to variable surface currents. As the stratification is near neutral equilibrium, the temperature contrasts are dissipated by vertical mixing leading to an increase of persistence as the interval p is increased.

The smaller body of data for Lake Superior is at least sufficient for the conclusion that persistence is much less than in Lake Ontario, for the months May to October. The unique condition of Lake Superior is that surface temperatures of 39° or 40° F. are still prevalent late in the warming phase. Shallow patches of warm water float about, thus giving a very variable surface temperature in a traverse and the rise of average temperature in the warming phase occurs by the increase and late merging of the patches. The low persistence is attributed to varying surface currents with varying temperature.

In November, there is little density stratification, and the persistence is about the same as in Lake Ontario. At a guess, it may remain the same as in Lake Ontario from November to April.

The Probable Error of Normals

The following formula has been given by Brooks (1948) for the standard deviation of means of independent groups of m observations. Within each group the persistence is constant, that is, $r = r_1^p$.

$$s^2 = \sigma^2\left[1 + \frac{2(m-1)}{m}r + \frac{2(m-2)}{m}r^2 + \ldots + \frac{r^{m-1}}{m}\right]$$
$$= \sigma^2\left[\frac{1+r}{m(1-r)} - \frac{2r(1-r^m)}{m^2(1-r)^2}\right]$$

The probable error of a normal formed from n years of observation with m equally spaced observations per month is,

$$\text{P.E.} = \frac{0.67\sigma}{n^{\frac{1}{2}}}\left[\frac{1+r}{m(1-r)} - \frac{2r(1-r^m)}{m^2(1-r)^2}\right]^{\frac{1}{2}}$$

where $r = r_1^{30/m}$

The P.E.'s of normals for Lake Ontario have been computed from the formula, assuming that the observations were equally spaced, which was not precisely true as they were daily observations with occasional gaps. This gave the following P.E.'s in degrees Fahrenheit for the twelve months, January to December:

.04 .04 .04 .03 .06 1.1 .6 .5 .6 .4 .3 .2

These P.E.'s are somewhat smaller than those found by the method next described. Considering that the persistence is not strictly constant physically and that the observations were not separated exactly equally, the agreement is good. It is therefore concluded that the persistence does not change materially after eight days.

The P.E.'s of most of the courses must be calculated in the usual manner, so all have been so treated including the course from Cobourg to Charlotte. Namely, the P.E. = .67 $\sigma_m/n^{\frac{1}{2}}$, where σ_m is the standard deviation of the averages of individual months in n years of observation. The results are given in Table IV. The P.E.'s for Lake Ontario, Cobourg to Charlotte, are smaller than most of the others because of the longer period of record, and the P.E.'s for Lake Superior, Fort William to Gros Cap, are smaller because of the smaller standard deviation.

TABLE IV. Probable errors of the normals, in degrees Fahrenheit.

Section	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Sup. 1-9	—	—	—	—	—	—	0.4	0.8	—	—	—	—
Sup. 10-22	—	—	—	—	0.2	0.3	0.3	0.4	0.2	0.4	0.3	—
Mich. 23-26	—	—	—	—	0.8	0.9	0.3	0.2	1.1	0.7	0.9	—
Mich. 27-39	—	—	—	—	0.7	0.8	0.5	0.7	0.4	0.8	0.6	—
Hur. 40-50	—	—	—	—	0.2	0.7	0.8	0.7	0.5	0.7	1.0	—
Hur. 51-61	—	—	—	—	0.3	0.8	0.9	0.4	0.5	0.6	0.5	—
Erie 62-72	—	—	—	1.4	1.2	0.6	1.0	0.5	0.4	0.6	0.8	—
Ont. 74-80	—	—	—	—	1.1	1.3	0.1	0.3	—	—	—	—
Ont. 81-88	—	—	—	0.9	1.0	1.2	0.8	1.3	0.8	0.5	1.3	—
Ont. 89-100	0.1	0.1	0.2	0.2	0.6	1.6	0.6	0.3	0.5	0.6	0.3	0.2
Average 23-88	—	—	—	1.1	0.8	0.9	0.6	0.6	0.5	0.6	0.7	—

TEMPERATURE FORECASTS FROM THE REGRESSION EQUATION

Quantitative evaluation of the persistence enables a prediction to be made of the temperature a few days subsequent to an actual observation. Supposing the anomaly on one day were x_o, the most probable anomaly p days later would be given by the regression equation $x_p = r_p x_o$. A scatter from the predicted anomalies

would occur in a number of predictions. This scatter would be measured by the standard deviation of $(x_p - r_p x_o)$, which is $\sigma_p = \sigma(1 - r_p^2)^{\frac{1}{2}}$.

It is suggested that any such prediction would become insignificant after σ_p exceeded $.9\sigma$. For this arbitrary criterion, $r_p = .44$. In Lake Ontario, $r_p = .9^p$, so the corresponding p would be 8 days. Predictions based on a single observation would have some value up to eight days; or one might say that observations eight days or more apart, are practically independent.

These considerations are meant to illustrate the possibility and limitations of a forecast based on one past temperature observation and the normal annual curve. Predictions could be improved by using more past observations and a more elaborate regression formula.

REVIEW

The normal temperatures given in Table I are the core of this paper, and the monthly maps, Figures 16 to 27, are the most informative graphical presentation. Lake Erie is the shallowest lake with the highest and earliest maximum temperature, and Lake Superior the deepest with the lowest and latest maximum. Normally the differences in temperature are distributed over a lake surface in a very persistent pattern, and the differences are great enough to reduce the average temperature of the whole lake to a numeral of little significance.

Probable errors of the monthly normals are mostly less than 1° F., and instrumental errors less. There may be a systematic difference in temperature between the surface and the level of the intake where the temperature was recorded. Recorded values may average as much as 1° F. low in the middle of the warming phase, but at other times the systematic difference is negligible.

When the prevailing temperature of a lake is between 32° and 50° F., the density changes only slightly with temperature, and mixing extends to the bottom. This results in a uniform temperature from surface to bottom, with little variation from day to day especially in winter. The temperature from December to June is strongly controlled by the depth, and isotherms tend to follow depth contours.

Currents in the lakes are driven by the winds, but are modified by the shore and bottom contours. The momentum of the currents keeps them very constant in spite of day-to-day changes in the wind. Therefore features of the temperature distribution dependent on currents are rather constant, but change with the seasons. Where surface currents converge, warm water gathers in midsummer and potential energy is added to the density distribution. Where surface currents leave the warm areas, they receive energy at the expense of the potential energy. In autumn, the spread of warm water out of the warm areas can be followed on the monthly maps, and reflects the conversion of the potential energy. Ultimately the energy is dissipated by friction. These conversions of energy are of interest because the potential energy is associated with thermal gradients; considering the interaction helps in mapping the isotherms.

The thermal capacity of the lakes being large, the surface temperature changes slowly in response to weather changes. An abnormal water temperature will persist in some measure for days, after a change from the weather which caused it.

The persistence has been assessed by calculating the serial correlation between readings a few days apart. Correlations over a twenty-four hour interval have been found from 0.5 to 0.99, with 0.9 a representative value. A high correlation is found in seasons favourable to deep mixing provided the temperature is fairly uniform through the probable depth of mixing. However, in April when the temperature is near 39°, the temperature of maximum density, the persistence is small over 24 hours. This results from varying currents of contrasting temperatures. The persistence in April is not exceptionally small when measured over four or eight days, a time sufficient to bring out the persistence associated with deep mixing. Observations of temperature eight days or more apart are practically independent. The advantage of more observations diminishes as the interval is reduced to a day or less, as the observations are not independent.

ACKNOWLEDGEMENTS

The author is indebted to Dr. John Patterson for directing the inauguration of the programme of observations on the Lakes, and to Mr. Andrew Thomson, his successor as Controller, Meteorological Division, Department of Transport, for directing after the war that the work should be completed, and for providing facilities.

Thanks is tendered to the steamship companies mentioned in the introduction, and to the chief engineers of the vessels, for their willing and interested co-operation. The assistant engineers, and deck officers who took weather observations at the same time, are also thanked.

Miss D. Isobel Bagnall, Meteorological Assistant, did most of the reading of thermograms and extracted the statistical results.

REFERENCES

Brooks, C. E. P. The variability of means of a series of observations. *Meteorol. Mag.*, **77**, 283-285, 1948.

Brunt, David. Physical and dynamical meteorology. Cambridge University Press, 1939.

Church, Phil. E. The annual temperature cycle of Lake Michigan. I. Cooling from late autumn to the terminal point, 1941-42. *Univ. Chicago, Dept. Meteorol., Misc. Rept.*, No. 4, 1942.
The annual temperature cycle of Lake Michigan. II. Spring warming and summer stationary periods, 1942. *Ibid.*, No. 18, 1945.

Hachey, H. B. Vertical temperature distribution in the Great Lakes. *MS. Rept. of the Biol. Sta., Fish. Res. Bd. Can.*, No. 397, 5 pp., 1950.

Harrington, Mark W. Surface currents of the Great Lakes. *U.S. Weather Bureau, Bull. B*, 1895.

Olsen, Franklin C. W. The currents of western Lake Erie. Ph.D. dissertation, Ohio State University, Columbus, Ohio, 1950.

Parmenter, Richard. Preliminary report on the cooperative survey of Lake Erie, season of 1928. Hydrography. *Bull. Buffalo Soc. Nat. Sci.*, **14**(3), 1929.

Sverdrup, H. A., Martin W. Johnson and Richard H. Fleming. The oceans: their physics, chemistry and general biology. New York: Prentice-Hall Inc., 1942.